A LABORATORY INVESTIGATION OF UNIFORM PROTECTIVE SAND FILTERS

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A LABORATORY INVESTIGATION OF

UNIFORM PROTECTIVE SAND FILTERS

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ABSTRACT

A laboratory investigation was conducted to determine whether previously developed empirical design criteria for filters are applicable to the design of uniform filters.

A series of tests were carried out using a modified permeameter. Various combinations of base and filter layers were placed in the modified permeameter and tested at various heads of water. The "limits of stability" of each combination of base and filter layer were determined. The soil samples were selected so there were definite relationships between the particle diameters of the base and filter layers. Definite relationships were employed so that the results could be compared with the results of previous studies.

The test program was arranged so that each sample was tested at heads of water of 5.25, 10.50, 15.75 and 21.00 feet. This was done so that the effect of the hydraulic gradient upon filter stability could be investigated.

Base layer samples with uniformity coefficients of 2.32, 3.0, 4.0 and effective grain size of 0.74 millimeters were tested in combination with uniform filters ranging in particle size from 0.34 to 0.073 millimeters. At each head of water and for each base layer sample the coarseness of the filter layer was increased until visual failure occurred.

The "limits of stability" of the uniform filter layers were checked by determining the amount of infiltration of base layer particles into the filter layer and by measuring the amount of flow through the test specimens. A qualitative measurement of base layer particle infiltration was obtained by the use of piezometers located along the side of the modified permeameter. The quantitative determination of base layer particle infiltration was made by performing sieve analyses on the uniform filter layers at the conclusion of each test.

The following conclusions were reached as a result of this investigation: (1) The amount of particle infiltration, while a condition of stability is being established between the base and filter layers, is proportional to the diameter of the filter layer particles. (2) The extent of base layer particle infiltration into a uniform filter layer is erratic and there is no definite relationship between depth of filter layer, head of water and the amount of base layer particle infiltration. (3) Maximum benefit is obtained with uniform filters when the ratio of the 50 per cent size of the base layer particles to the 50 per cent size of the filter layer particles is between the limits of 4 and 11. (4) The design criteria presented by Dr. Karl Terzaghi are adequate for the design of uniform filters.

During the investigation and the analyses of results the following questions arose and are suggested as topics for further research: (1) Can a relationship be established between the uniformity coefficient of the base layer particle size and the uniform filter layer particle size which will aid in the design of uniform filters? (2) What effect have sudden shocks upon the stability of uniform filters? (3) Will particles that infiltrate into the filter layer while a "condition of stability" is being established pass completely through the filter layer? And is this movement a function of the diameter of the particles, head of water and time or of the depth of the filter layer?

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CHAPTER I

INTRODUCTION

General Background.--Numerous structures have failed because of inadequate protection of the soil upon which the foundation rests. Uplift pressures, erosion of the fine soil in the foundation stratum (soil to be protected) and frost action have all caused foundation failures. These hazards can sometimes be eliminated by protecting the foundation stratum with layers of soil that are more pervious than the foundation layer. This investigation was conducted to determine the effectiveness of one type of these pervious layers, uniformly graded layers.

In this thesis the following terminology was adopted for materials comprising each of the two layers of the test specimen: The first layer, which represents the foundation stratum, is called the "base layer". It is the stratum to be protected. The second and more pervious layer is referred to as the "filter layer".

A filter is a layer of soil which is used to prevent erosion of the soil being filtered and which also offers less resistance to flowing water than does the soil being filtered. This is accomplished by protecting the base using soil more coarsely graded than the base layer. This coarser filter layer is placed adjacent to the base layer. As water flows first through the base layer and then the filter layer, particles from the base layer are carried into the pores of the filter. If the filter is adequate, these particles will collect in the pores of the filter layer near the point of contact of filter and base layers. This particle movement effectively reduces pore diameter of the filter and thereby prevents the continuation of erosion of the base because the filter material particles are larger and heavier and will not be eroded as easily (see Fig. 1). This process continues until even the smallest particles in the base are held in position due to the "build-up" of particles. This condition is referred to as a "condition of stability". Only the diameter of the pores of the filter adjacent to the base layer are effectively reduced, the rest of the filter remains porous and offers less resistance to flowing water than does the base layer.

A properly designed filter must satisfy two requirements: (1) particles of the filter layer must be sufficiently fine to prevent any movement of the base layer through the filter or to prevent any of the material from the base layer from clogging the filter, and (2) particles of the filter layer must be sufficiently coarse so that the structure of the filter remains stable under all conditions, and so that resistance against water flowing through the filter layer is kept to a minimum. Where frost damage is possible the filter layer must be thick enough to provide adequate insulation for the base layer.

One of the following types of filters is usually employed for foundation stratum protection. The first type is the uniform filter

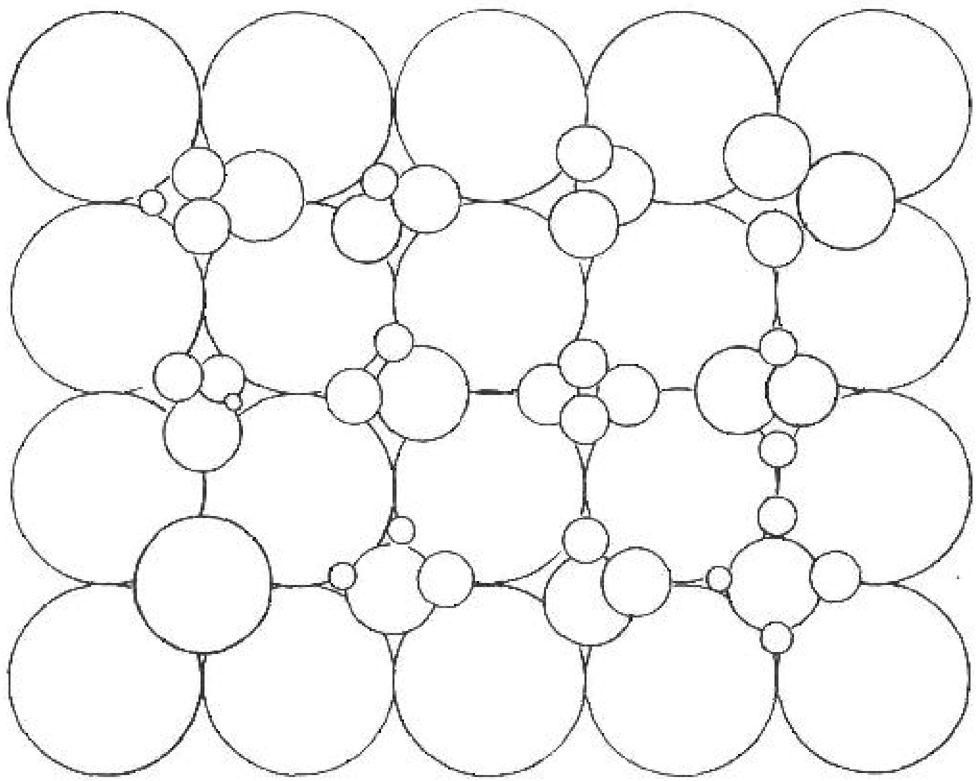

FIG. 1 CONDITION OF FILTER STABILITY

in which all the particles are approximately the same size and shape. The second type is the graded filter in which the soil is usually a naturally graded sand with a gradation curve that satisfies design requirements. The third and most complex type is the composite filter. This filter is composed of several layers of uniform filters with the particle size in each layer having a definite relationship with the preceding layer. Thus the composite filter has increasing perviousness in the direction of flow, with the result that the resistance to flow is less than in other types.

Purpose of the Investigation.--This investigation was conducted to determine whether previously developed empirical design criteria for filter design are applicable to uniform filters. The limits of stability for the uniform filters tested were checked by: (1) determining the amount of infiltration of the base layer into the filter, and (2) by measuring the discharge through the filter at various heads of water. A qualitative measurement of particle infiltration of base material into the filter layer was obtained by the use of piezometers located at various points along the test specimen. The quantitative determination of particle infiltration was accomplished by sieve analyses of the filter layer at the completion of each test.

Previous Studies.--Until 1928 filters were designed solely from past experience. Protective filters were not very successful until the development of modern soil mechanics when filter design was placed on a scientific level. Dr. Karl Terzaghi is credited with having been the first to use weighted filters (1). He used the filters to repair concrete aprons of overflow dams and was subsequently issued a patent.

Based upon the requirements of both the base layer and the filter layer, the following criteria for the design of filters were presented by Dr. Terzaghi:

$$\frac{D_{15} \text{ of the filter}}{D_{15} \text{ of the base}} \geq 4 \quad \text{(Eq. 1)}$$

$$\frac{D_{15} \text{ of the filter}}{D_{85} \text{ of the base}} \leq 4 \quad \text{(Eq. 2)}$$

in which D_{15} = 15 per cent size by weight

D_{85} = 85 per cent size by weight

Equations (1) and (2) were derived to satisfy filter requirements (1) and (2) respectively.

In order to facilitate the design of filters, of which many were required by the United States Bureau of Reclamation, an intensive study was conducted in the Soil Mechanics Laboratory of the Graduate Division of Engineering of Harvard University (2). G. E. Bertram conducted the study during the academic year of 1938-1939. Bertram's results verified the ratios of stability that had been presented by Dr. Terzaghi.

The United States Army Corps of Engineers conducted a series of experiments on filters in 1948. After a large number of tests the grain size curves of the base and filter layers which remained stable after testing were analyzed. The Corps presented an empirical relationship, based on the grain size curves for combinations of base and filter layers that remained stable during the tests. The grain size curves for the stable combinations were approximately parallel and at equal ordinates for per cent finer than the ratio of the particle sizes was approximately 25 (3). It was also recommended that filter material for drainage purposes should be densely packed.

Some more recent work has been carried out at the Earth Laboratory of the Bureau of Reclamation in Denver, Colorado, under the direction of K. P. Karpoff, materials engineer (4). Karpoff concluded that the physical properties of filter material is characterized mainly by the mean grain size, which is approximately the 50 per cent size on the grain size curve.[a] The mean grain size is the mean size of all the particles. Because for most naturally graded base material the mean grain size falls between the 40 and 60 per cent values on the grain size curve, Karpoff chose the relationship between the 50 per cent size of the filter material to the 50 per cent size of the base material as a control factor for the investigation of the stability of uniformly graded filters. Karpoff's results indicated that this ratio should fall between the limits of 5 and 10 for stability with uniform filters.

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[a]The reader who is unfamiliar with the term uniform soil is referred to article 3 in Soil Mechanics in Engineering Practice by Terzaghi and Peck, John Wiley and Sons, Inc., 1948.

CHAPTER II

MATERIALS AND EQUIPMENT

The materials and equipment used in this thesis are listed and described as follows.

Base Layer Materials.—The base layer materials were artificially graded quartz sands with subangular to angular grains. The base layer material physical properties are as follows:

Specific gravity of soil solids. 2.66

Effective grain size. . . . 0.073 and 0.074 millimeters

Uniformity coefficients. 2.32, 3.00, 4.00

Gradation. . . . . see Fig. (2)

Filter Layer Materials.—The filter layer material was subangular to angular quartz sand with a specific gravity of 2.66. The filter layer material was separated from a naturally graded sand by mechanical sieving using United States Standard Sieves. The six sizes of filters tested are listed in Table 1.

Table 1

Filter Layer Material Grain Sizes

Filter	Passing	Retained On
1	3	4
2	6	8
3	9	10
4	10	12
5	16	20
6	30	40

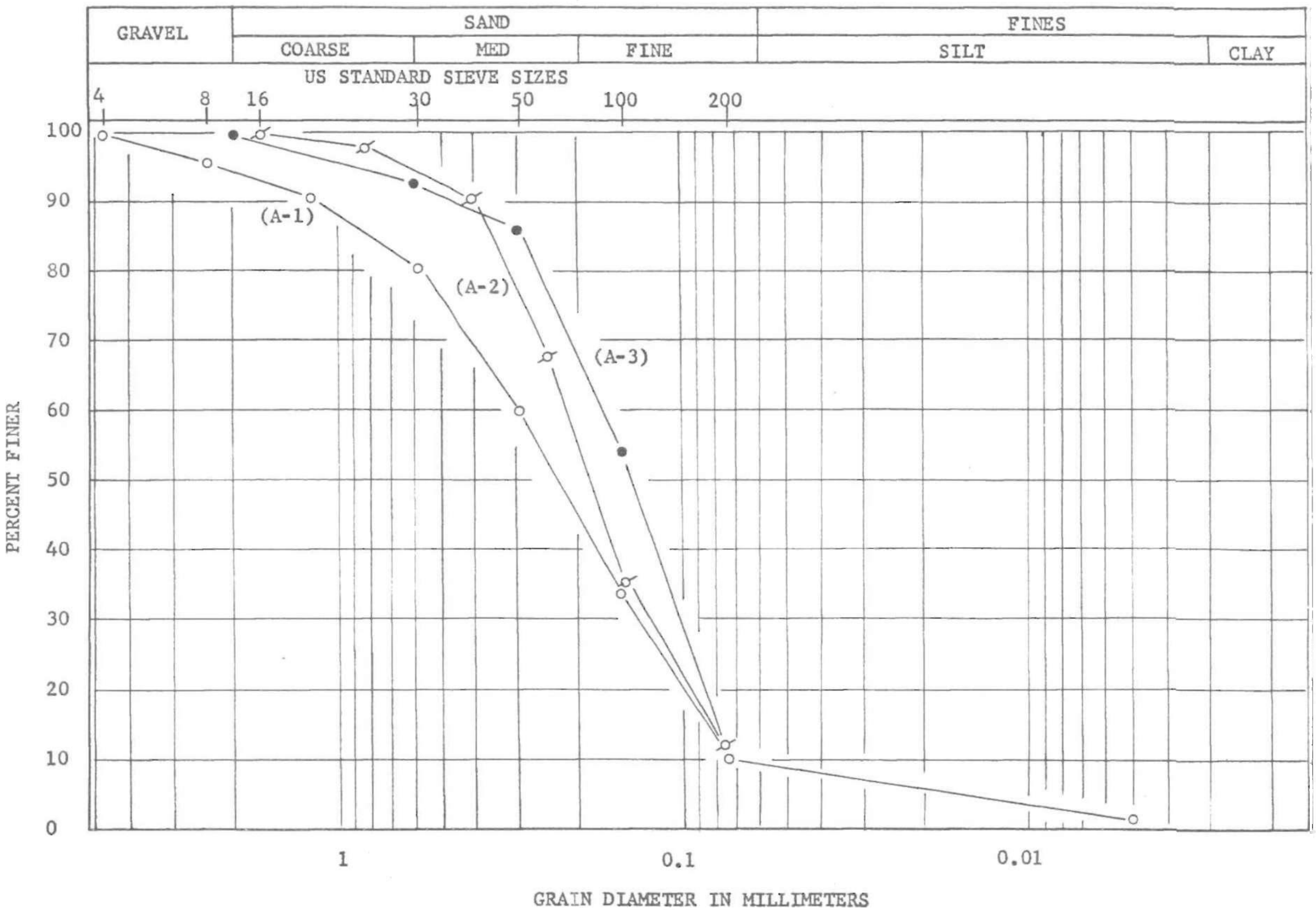

FIG. 2 GRAIN SIZE CURVES FOR BASE MATERIALS

Test Cylinder.--The test equipment consisted of a "Lucite" cylinder fourteen inches in length with an inside diameter of four inches.[b] Each end of the cylinder was sealed with an aluminum plate, six inches square by 0.5 inch thick. The cylinder was fitted into 0.25-inch-deep circular grooves in the aluminum plates. There were two openings in the upper plate, one for de-airing the test samples and the other for the water supply line. The single opening in the lower plate was used both to saturate the sample and as the discharge outlet. Along the length of the cylinder were located five sets of piezometers. Two piezometers were placed at each level to minimize the effect of variations in density of the sample upon the piezometric readings (see Fig. 3). "Lucite" tubing was selected for the test cylinder so that the samples could be visually observed during the tests.

Manifold and Manometer.--The piezometers in the test cylinder were connected to a "Lucite" manifold by a system of small diameter tubes (see Figs. 4 and 5). The manifold was connected to a manometer with similar tubing. The manifold was used so that the difference in piezometric head between the reference set and any other set of piezometers could be read directly during the tests.

Water Supply.--Water for the tests was supplied from a five-gallon glass carboy. The carboy was connected to a compressed air supply tank with an air valve pressure regulator on the line (see Fig. 5). With this system the air pressure could be controlled to obtain the

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[b] The four-inch inside diameter "Lucite" cylinder was selected in accordance with the results of similar experiments conducted by G. E. Bertram. Bertram discovered that the diameter of the test cylinder has no noticeable effect upon the test results.

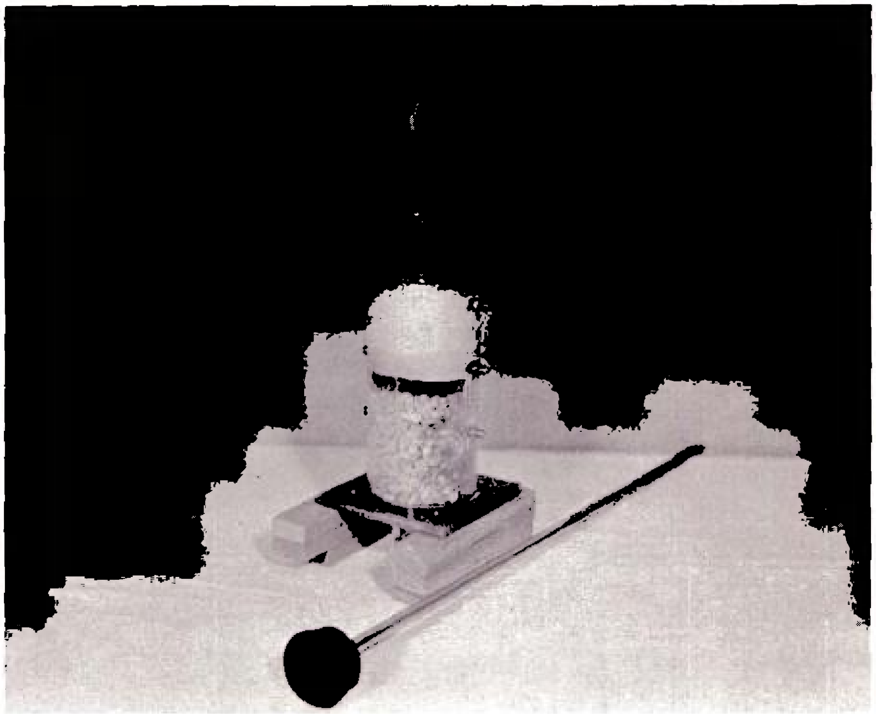

FIG. 3 TEST CYLINDER BEING PREPARED FOR TESTING

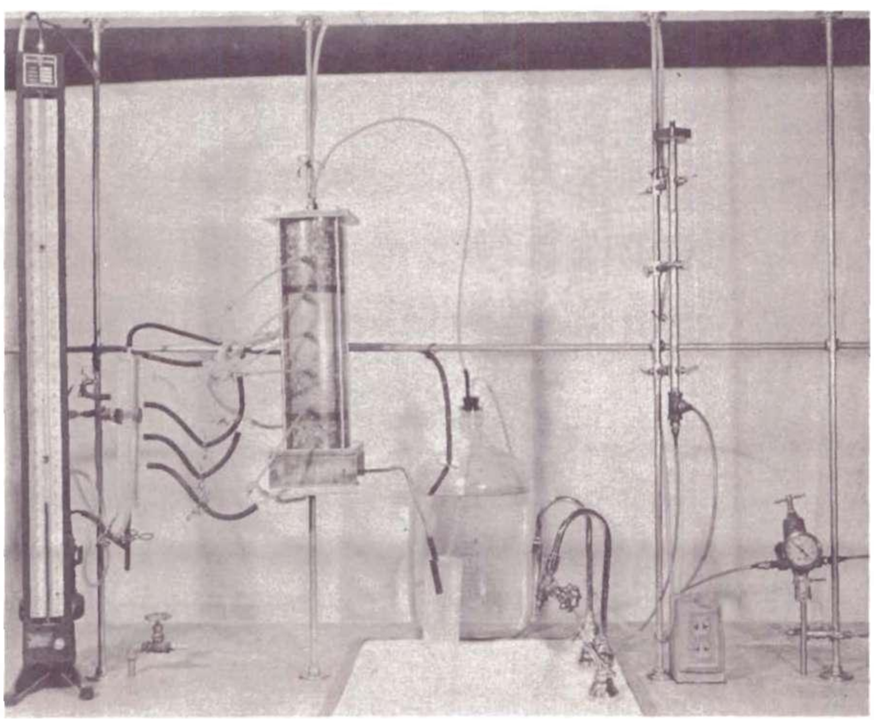

FIG. 4 TESTING A SAMPLE

heads that were desired. A preliminary set of tests were conducted in order to check the equipment. Some difficulty was encountered in keeping a constant head with the air pressure regulator alone. The container for the water supply was small, and as a result even small amounts of flow caused a large percentage of volume change of the air in the container. This change in volume caused considerable decreases in air pressure in the water supply container, thereby reducing the head. The air pressure regulator could not compensate for the decrease in air pressure. A "blow-off" valve was placed on the compressed air line between the air pressure regulator and the water supply (see Fig. 6). The weight on the valve could be adjusted to give any desired head. Air was then forced through the system so that the "blow-off" valve opened and closed at a very rapid rate. This system amply compensated for the decrease in the head due to the expanding air in the water supply container. The system did not compensate for head loss due to lowering in elevation of the surface of the water supply. However, this effect on the piezometer readings was negligible.

Sieve Equipment.--All sieving was done in a "Ro-Tap" sieve shaker using standard calibrated sieves.

Compaction Equipment.--All samples were compacted by hand using the rubber tamper shown in Fig. 3.

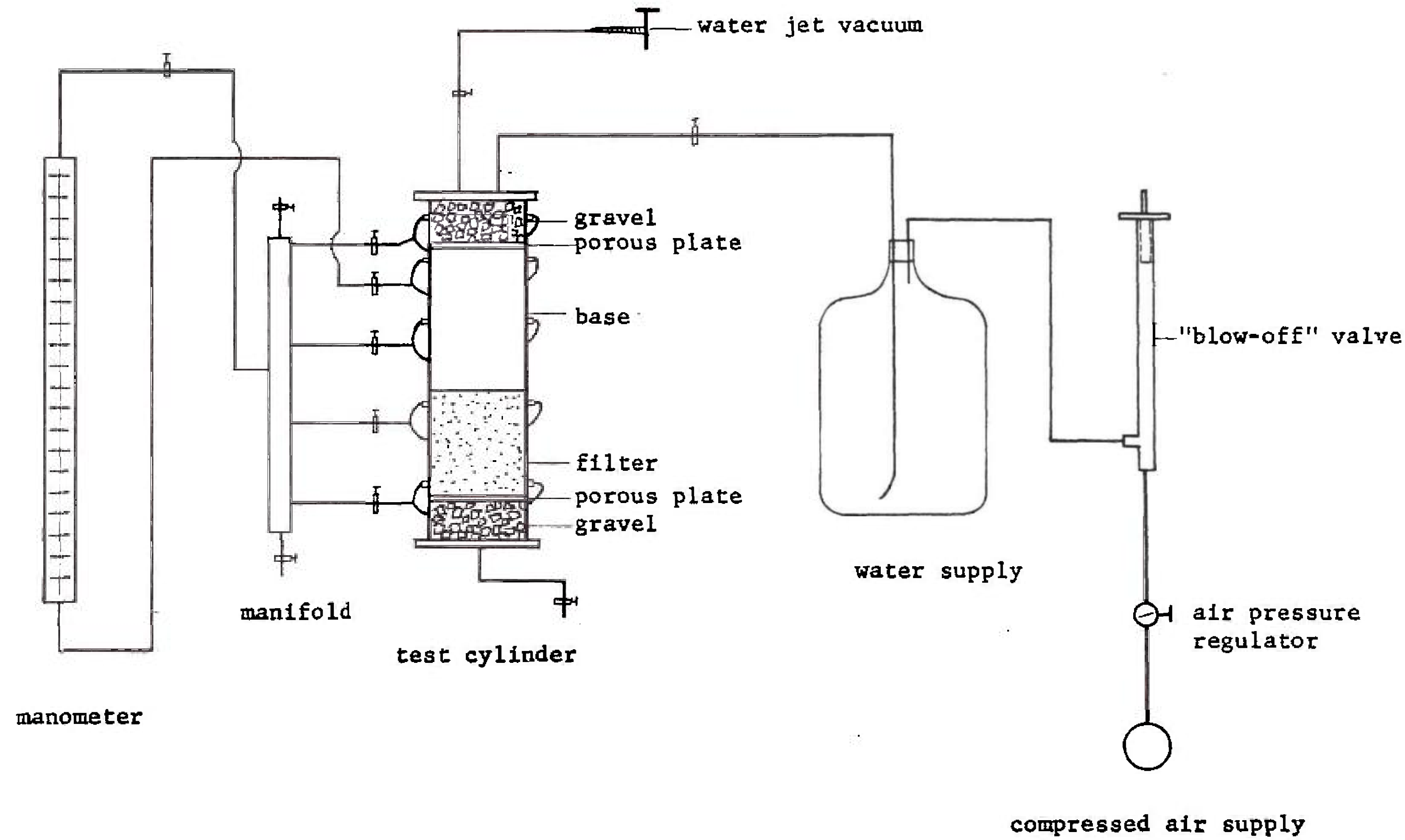

FIG. 5 SCHEMATIC DIAGRAM OF TEST EQUIPMENT

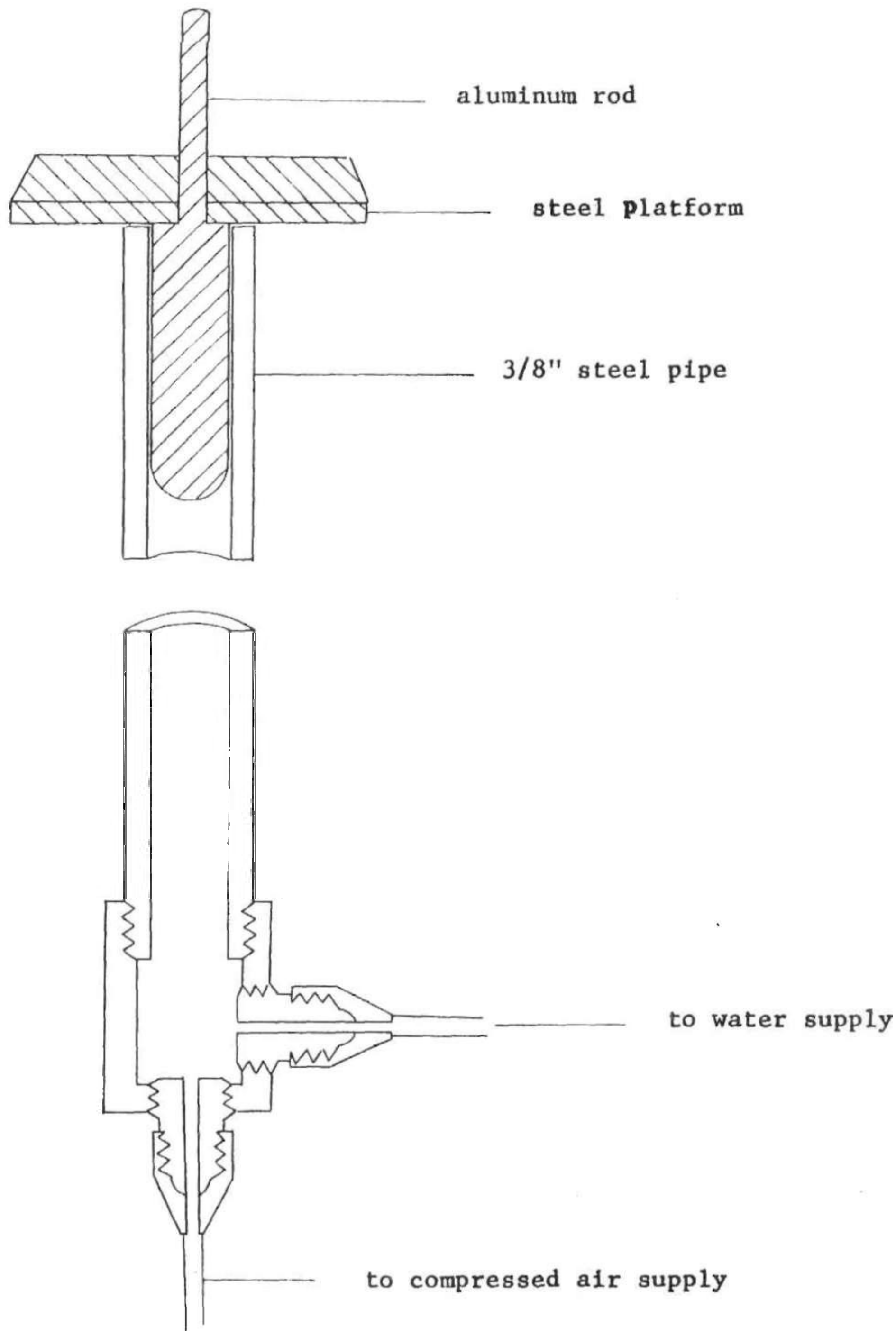

FIG. 6 CONSTANT HEAD DEVICE

CHAPTER III

PROCEDURE

Preliminary.--Naturally graded sands were brought into the soils laboratory and allowed to air dry thoroughly. The sand was separated into various particle sizes using standard sets of calibrated sieves and a "Ro-Tap" sieve shaker. The samples were graded using three-hundred gram batches. Each batch was allowed to remain in the sieve shaker for fifteen minutes. The samples were then washed on the proper size sieves to remove dust and clay particles; dried in ovens; and stored in suitable containers. Difficulty was encountered in obtaining material finer than a No. 100 U.S. Standard sieve. Larger particles were placed in a Los Angeles abrasion machine and crushed to the desired size. This material was washed, oven dried, and stored in suitable containers.

The specific gravity of the samples was determined and the grains were examined and classified as to grain shape (5). A wet hydrometer analysis was performed on the material finer than a No. 200 U.S. Standard sieve to determine the particle sizes of this fine material.

Preparation of Base Materials.--In preparing the mixtures for the base layer materials, grain size curves with the desired shape, effective size, and uniformity coefficients were plotted. The percentage of each size of particle was obtained from the curves (see Fig. 2). The proper amount of each particle size was weighed to the nearest 0.05 gram and placed in a flat mixing pan. Each sample was then thoroughly mixed by hand. These samples were then placed in suitable containers and stored until needed.

Preparation of Test Cylinder, Testing, and Measuring.--Samples in the test cylinder were prepared in the following manner. (1) The aluminum top was placed on the wooden compaction blocks. A rubber washer was placed in the machined groove in the aluminum top, and the "Lucite" cylinder was then fitted into the groove. (2) Five inches of crushed granite, particles approximately one-half inch in diameter, was placed into the cylinder in three equal layers. Each layer was compacted with the rubber tamper. The layer of granite was used as a filler material in order to eliminate the effect of the abrupt expansion into the test cylinder and to obtain more uniform flow conditions. The readings from the upper set of piezometers were disregarded because of the proximity of these piezometers and the water supply inlet. The second set of piezometers was used as the reference piezometers. (3) On top of the crushed granite was placed a one-half inch thick porous plate four inches in diameter. The purpose of the plate was to separate the granite filler and the base layer material and to aid in establishing uniform flow conditions. (4) A forty-mesh circular wire screen four inches in diameter was placed on top of the porous plate. The screens were used to prevent any movement of base layer material into the granite filler during compaction and saturation of the samples. (5) The container holding the oven-dried base material was weighed to the nearest 0.01 pound. The base material was then compacted into the cylinder to a depth of four inches. Compaction was in three layers. (6) The soil remaining in the container was again weighed to the nearest 0.01 pound, the difference in weights obtained in (5) and (6) being equal to the weight of the soil in the base layer. (7) The filter layer was then placed in the cylinder following the same procedure outlined in steps (5) and (6). (8) A forty-mesh circular screen four inches in diameter was then placed on top of the filter layer. Over the screen was placed a porous plate, the same as in step (3). (9) A two-inch layer of granite, the same as in step (2), was compacted into the cylinder in one layer. (10) A rubber gasket was placed around the edge of the cylinder, and the machined groove in the bottom aluminum plate was fitted to the cylinder. The four tension rods joining the aluminum plates were then tightened. (11) The test cylinder was removed from the compaction block and placed on the platform provided for testing. (12) The piezometers, water supply line, and vacuum line were attached to the cylinder. The cylinder was checked for airtightness. Adjustments were made with both the tension rods and lines attached to the cylinder until the cylinder was airtight. (13) The samples were evacuated using a water jet vacuum and then saturated from the bottom upward. Saturation of the sample in an upward direction and the preparation of the sample "upside down" was used so there would be no tendency for the particles from the base layer to infiltrate into the filter layer until the test was begun. (14) When the sample was saturated, weights that would produce a head of one-inch mercury were placed upon the platform of the "blow-off" valve and the platform made to open and close rapidly by adjusting the air pressure regulator. Water was permitted to flow through the sample for a duration of four hours at this low head.[c] It was thought the employing of a low head during saturation would have a negligible effect on particle movement. (15) The heights of both filter and base layers were then measured to the nearest 0.05 inch. An average height was obtained by taking measurements at four locations. Using the average height and the weight of the material in each layer, the density of the layers was calculated. (16) After complete air segregation, weights that would give the desired head were placed on the platform of the "blow-off" valve, and the air pressure regulator adjusted to give the desired head. Each combination of base and filter was tested at heads of 5.25, 10.50, 15.75, and 21.00 feet of water. All heads were checked at the reference set of piezometers. (17) As soon as possible after the test was started, approximately three minutes, the difference in piezometric heads between the reference piezometers and the other sets of piezometers were recorded. The discharge through the test cylinder was also measured. (18) Each test was two hours in duration.[d] After two hours the piezometric readings were again recorded and the discharge measured. When necessary, the test was discontinued and water added to the water supply container. (19) The test apparatus was disassembled and the test

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[c]Bertram discovered that all noticeable influence of air segregation upon permeability occurred within four hours after water was permitted to flow through the sample. Since it was desired to obtain the influence of particle movement alone upon permeability, all samples were saturated and water allowed to flow through them for four hours before the actual test.

[d]Bertram's experiments revealed that all appreciable particle movement occurs within one hour after the beginning of the test. To insure that all particle movement did occur, these tests were run for a period of two hours.

sample extruded from the "Lucite" cylinder using the loading machine shown in Fig. 7. The filter layer was extruded in four increments, each one inch long. Each increment was placed in a porcelain evaporating dish and oven-dried. A section of the base layer in contact with the filter was placed into an evaporating dish and oven-dried. (20) After the samples were thoroughly dried, the porcelain evaporating dishes containing the filter layer increments were weighed to the nearest 0.05 gram. The samples were then placed into a "Ro-Tap" sieve shaker for ten minutes. The sieves used with each size of filter layer are shown in Table 2 in the Appendix. (21) Each empty porcelain dish was weighed to the nearest 0.05 gram. The difference of the weights obtained in steps (20) and (21) equaled the weight of each increment of filter layer. (22) After each increment of filter was sieved and the material passing the finest sieve was weighed to the nearest 0.005 gram, the percentage of base material to filter material in each increment was calculated. (23) A grain size distribution was performed on the section of base layer material obtained in step (19). Each sample was sieved for fifteen minutes in a "Ro-Tap" sieve machine. The weight of the material retained on each sieve was determined to the nearest 0.05 gram and the values for a grain size curve calculated. A tabulated list of the test data is found in Table 4 in the Appendix.

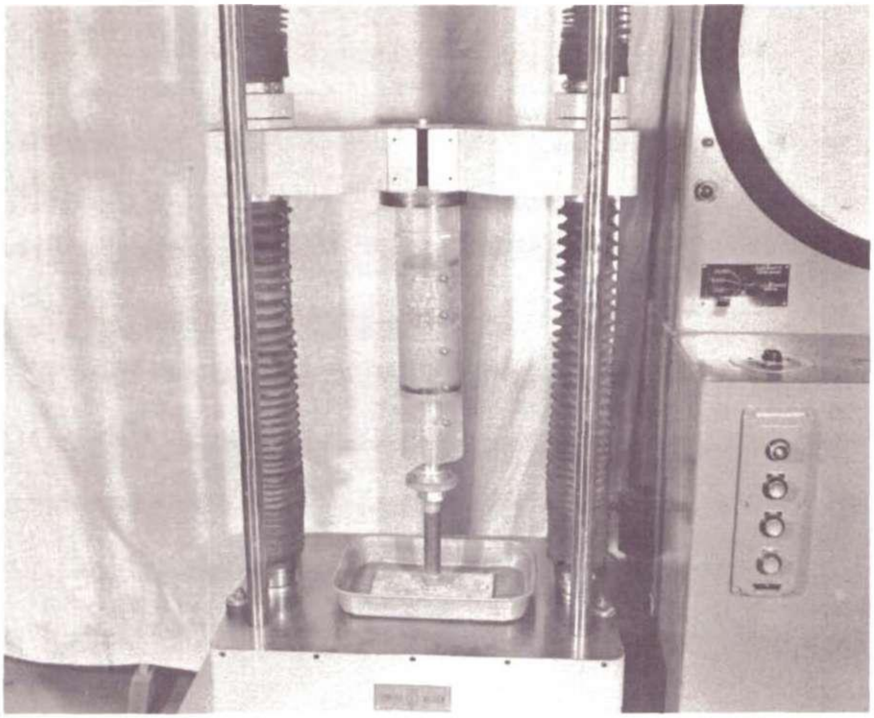


FIG. 7 EXTRUDING OF TEST SAMPLES FROM TEST CYLINDER

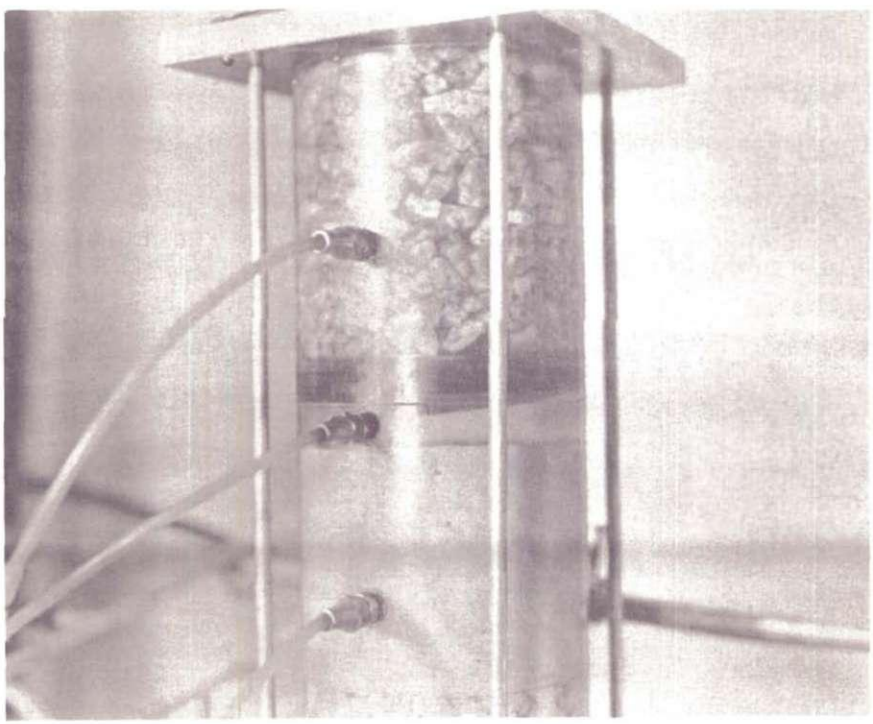


FIG. 8 VISIBLE FAILURE OF TEST SAMPLE

CHAPTER IV

DISCUSSION OF RESULTS

Test Results.--A summary of the test data appears in the Appendix as Tables 5, 6, and 7. The test data are discussed in accordance with the methods of measurement employed - infiltration, flow, and piezometric readings. Correlation of the results with regard to the methods of measurement is discussed. All test results are discussed with relationship to "limits for stability" for uniform grain size filters, and these limits are compared with the limits obtained in previous investigations.

Computed densities for both base and filter layers revealed that the compaction of the samples by hand tamping gave consistent values of density for each particular base sample and filter size. The maximum variation for two samples in the same group was 5.6 per cent by weight. It is assumed that the small variation in density between similar samples would have a negligible effect upon the test results. There was some indication that the lower porous plate may have affected the infiltration characteristics. The tests, as indicated in Table 3, were conducted without the lower porous plate. Comparison of these results with tests conducted with the lower porous plate indicates that the lower porous plate had no noticeable effect upon the infiltration characteristics during the two hour test period.

Infiltration.--The analysis of infiltration began by calculating the total weight of base layer material in the filter layer. These values are tabulated in Table 4. The base layer material in the first increment of the filter layer was neglected because the portion of the filter which was in contact with the base layer could not be accurately separated. Inspection of the values in Table 4 indicates that there is a greater amount of infiltration with increasing coarseness of the filter layer material. Non-conformance of values in Table 4 may be the result of jarring the test cylinder during its set-up, errors in weighing, or fracture of filter layer particles during the sieving process.

To obtain a clear picture of the relationship between per cent infiltration, depth of filter, and head of water, curves with head versus per cent infiltration of base layer material were plotted. A separate curve was plotted for each increment of filter. These curves appear in the Appendix as Figs. 10 through 21. Inspection of these curves indicates there is no fixed relationship between depth of filter, head of water, and per cent infiltration of base layer material for uniform filters. The author offers the following explanation. Before a "condition of stability" is established between a base and filter layer, there will be some infiltration of base material in the filter layer. The amount of infiltration is greater as the coarseness of the filter is increased. This infiltrated material will eventually pass completely through the filter layer. The movement will be a function of the diameter of the particles, flow, and time or depth of filter. Base layer particles were found distributed throughout the filter layer when the tests were ended after two hours. This increment of time was not sufficient to allow all the infiltrated base layer particles to collect on the lower porous plate. The varying amounts of infiltration throughout the filter layer's depth are attributed to the fact that base layer particles had various diameters and as a result the particle movement through the filter layer was erratic. During the tests in which the lower porous plate was removed, the discharge was sometimes cloudy. This was probably the finest base layer material, which rapidly passed through the filter layer since the rate of particle movement is inversely proportional to the diameter of the soil particles. It is conceded that some base layer material would be trapped in the cavities of the filter and would never pass completely through the filter layer. The amount of this material is insignificant and its movement ceases within a short time.

Flow.--The analysis of flow began by computing a relationship between the 50 per cent size of the filter layer material to the 50 per cent size of the base layer material (6). These relationships are listed in Table 3. Curves of the 50 per cent size ratio versus flow were then plotted. These curves appear as Figs. 9, 10, and 11. Inspection of these curves reveals that between the limits of 4 and 11 of the 50 per cent size ratio the flow reaches a maximum, while a "condition of stability" is still maintained. The author cannot offer any plausible explanation for this occurrence. Similar curves were obtained by Karpoff during his experiments (7).

Piezometric Readings.--The piezometric readings for each test are listed in Table 7 of the Appendix. The author could not establish any relationships between piezometric readings and filter stability. Piezometers

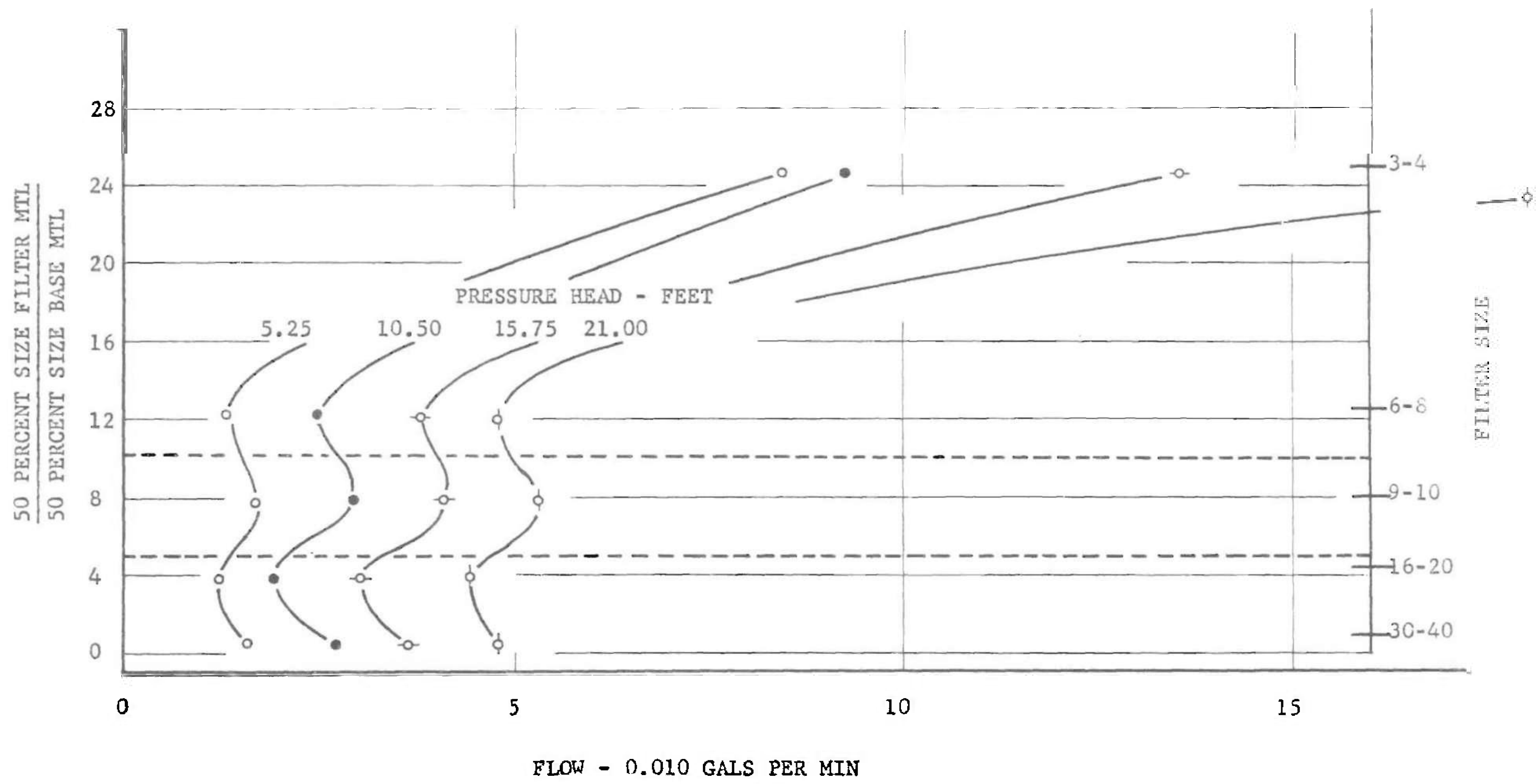


FIG. 9 FLOW CURVES FOR BASE MATERIAL (A-1)

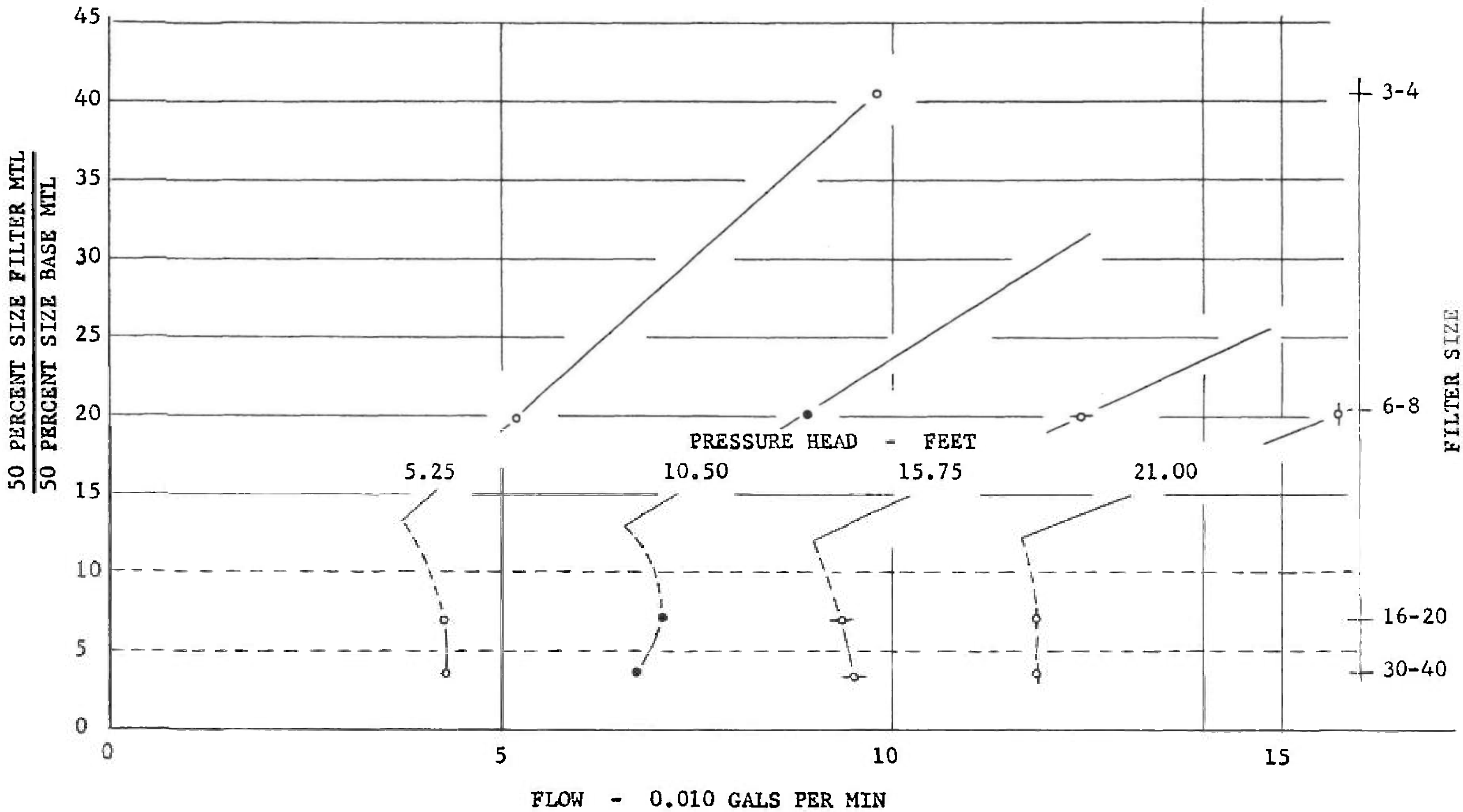


FIG. 10 FLOW CURVES FOR BASE MATERIAL (A-2)

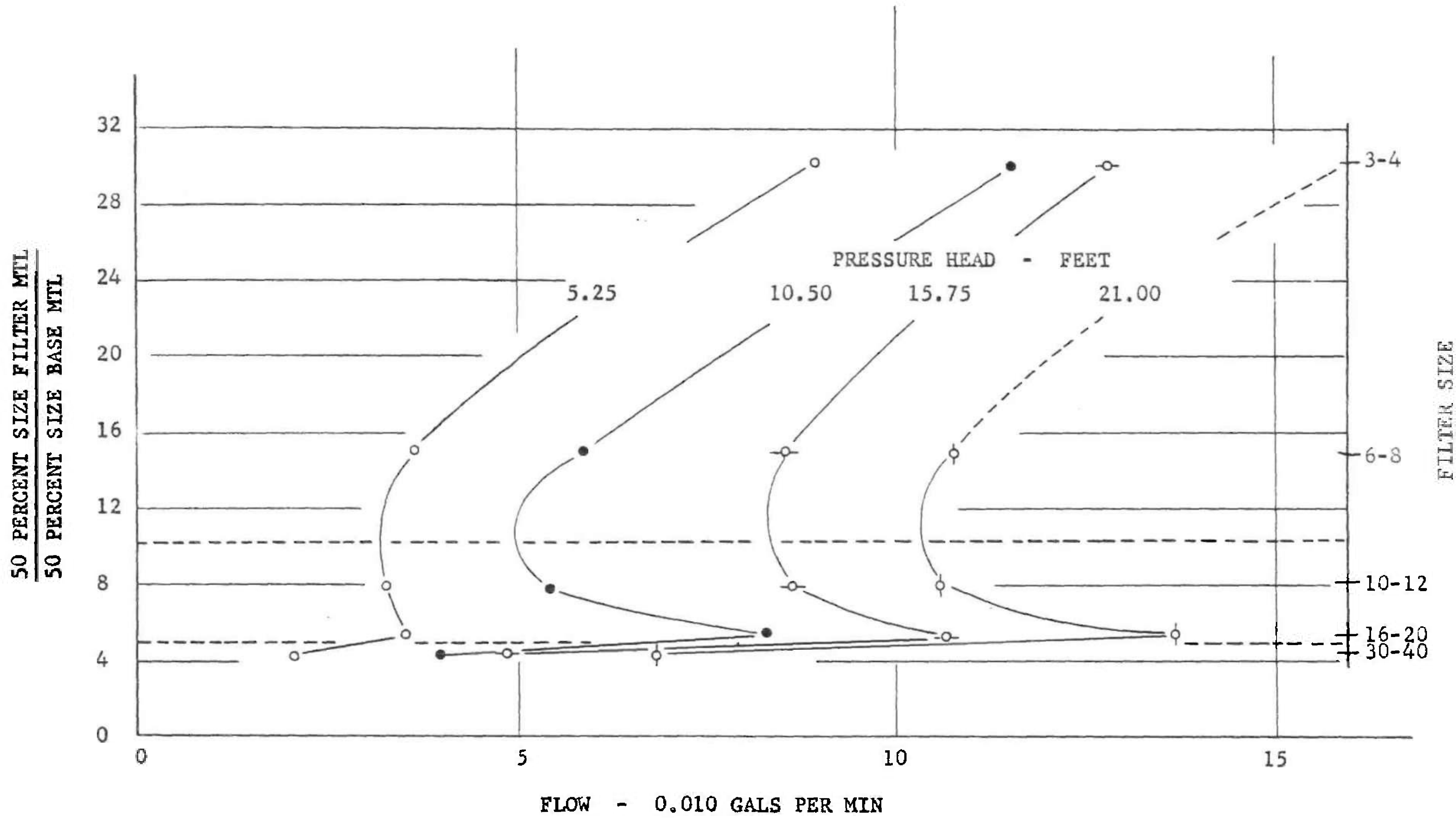


FIG. 11 FLOW CURVES FOR BASE MATERIAL (A-3)

should have been spaced closer together and piezometric readings made at short intervals during each test. In this way the actions of the infiltrated base layer material could be observed and the theory of particles passing completely through the filter layer investigated. A more sensitive manometer should be used in future investigations.

Comparison of Results.--For comparing the results with the results of previous investigations the ratio of Dr. Terzaghi's equations as shown on page 5 were computed. They are found in Table 4 of the Appendix. The ratios at the "limit of stability" for equations (1) and (2) were found to be 28 and 5 respectively. These values agree with those presented by Dr. Terzaghi (8) and Mr. Bertram (9).

Maximum values of flow with particle stability are obtained when the ratio of the 50 per cent size of the base layer and filter layer particles is 4 through 11. These values compare favorably to the values 5 and 10 obtained by Karpoff for similar tests (10).

Use of "Lucite" cylinder permitted visual inspection of the sample during the tests. Particle movements could be clearly seen. Fig. 6 shows a photograph of the failure of a 3-4 size filter layer and an A-2 base layer. At the start of the test the upper porous plate was in contact with the base layer. Similar failures occurred during all tests using a 3-4 filter layer.

CHAPTER V

CONCLUSIONS

The following conclusions were reached as a result of this investigation.

(1) The amount of infiltration, while particle stability is established between base and filter layers, is proportional to the diameter of the filter layer particles.

(2) The extent of base layer particle infiltration into a uniform filter layer is erratic and there is no relationship between depth of filter layer, hydraulic gradient, and the amount of base layer particle infiltration.

(3) Maximum benefit is obtained with uniform filters when the ratio of the 50 per cent size of the filter layer particles to the 50 per cent size of the base layer particles is between the limits of 4 and 11.

(4) The design criteria presented by Dr. Karl Terzaghi are adequate for the design of uniform filters.

CHAPTER VI

RECOMMENDATIONS

During the investigation and the analysis of results the following questions arose and are suggested as topics for future research.

(1) Can a relationship be established between the uniformity coefficient of the base layer particle size and the uniform filter particle size to aid in filter design?

(2) What effect have sudden shocks upon the stability between base and filter layers?

(3) Will material that infiltrates into the filter while a "condition of stability" is established pass completely through the filter layer? And is this movement a function of the diameter of the particles, flow, and time or of the depth of filter layer?

A P P E N D I X

TABLE 2

Sieves Used to Determine the Amount of Infiltration of Base Material Into the Filter Layer

Filter Size		Sieves Used in Analysis		
Passing	Retained On	1	2	3
3	4	3	4	16
6	8	6	8	20
9	10	9	10	20
10	12	10	12	20
16	20	16	20	50
30	40	30	40	80

TABLE 3

Tests Conducted

Base Material (Noncohesive)	Filter 3-4	Filter 6-8	Filter 9-10	Filter 10-12	Filter 16-20	Filter 30-40
A-1 S - curve[a] 0.002[b] No. 4 Max C_u = 4 D_{10} = No. 200 Head-5.25, 10.50, 15.75, 21.00	Stright[a] No. 4 Min[b] No. 3 Max R' = 24.87[d] R" = 59.39[e] R* = 6.31[f]	Stright[a] No. 8 Min[b] No. 6 Max R' = 12.48[d] R" = 28.52[e] R* = 3.03[f] PR @ 5.25	Stright[a] No. 10 Min[b] No. 9 Max R' = 8.00[d] R" = 20.3[e] R* = 2.16[f]		Stright[a] No. 20 Min[b] No. 16 Max R' = 4.43[d] R" = 10.51[e] R* = 1.11[f]	Stright[a] No. 40 Min[b] No. 30 Max R' = 2.20[d] R" = 5.24[e] R* = 0.56[f] PR @ 15.75
A-2 S - curve[a] 0.002[b] No. 16 Max C_u = 2.32 D_{10} = No. 200 Head-5.25, 10.50, 15.75, 21.00	Stright[a] No. 4 Min[b] No. 3 Max R' = 40.86[d] R" = 63.10[e] R* = 17.40[f]	Stright[a] No. 8 Min[b] No. 6 Max R' = 20.56[d] R" = 30.30[e] R* = 8.36[f] PR @ 5.25			Stright[a] No. 20 Min[b] No. 16 Max R' = 7.29[d] R" = 11.16[e] R* = 3.08[f]	Stright[a] No. 40 Min[b] No. 30 Max R' = 3.81[d] R" = 5.58[e] R* = 1.53[f]
A-3 S - curve[a] 0.002[b] No. 10 Max C_u = 3.0 D_{10} = No. 200 Head-5.25, 10.50, 15.75, 21.00	Stright[a] No. 4 Min[b] No. 3 Max R' = 30.11[d] R" = 59.39[e] R* = 14.02[f]	Stright[a] No. 8 Min[b] No. 6 Max R' = 15.11[d] R" = 28.52[e] R* = 5.24[f]		Stright[a] No. 12 Min[b] No. 10 Max R' = 8.13[d] R" = 1.71[e] R* = 4.03[f]	Stright[a] No. 20 Min[b] No. 16 Max R' = 5.36[d] R" = 10.51[e] R* = 2.48[f] PR @ 10.50	Stright[a] No. 40 Min[b] No. 30 Max R' = 4.63[d] R" = 5.24[e] R* = 1.24[f]

[a]Shape of the gradation curve

[b]Minimum and maximum grain size

[c]PR = Lower porous plate removed during test at this head

[d]$R' = \frac{\text{50 \% size filter material}}{\text{50 \% size base material}}$

[e]$R'' = \frac{\text{15 \% size filter material}}{\text{15 \% size base material}}$

[f]$R^* = \frac{\text{15 \% size filter material}}{\text{85 \% size base material}}$

TABLE 4

Weight of Infiltrated Base Material* in Filter Layer (grams)

Base Material A-1

Head (ft)	Filter Size				
	3-4	6-8	9-10	16-20	30-40
5.25	5.56	0.38	1.02	1.26	0.44
10.50	12.54	0.92	0.92	1.14	0.35
15.75	15.63	1.31	1.15	1.09	0.34
21.00	-	2.16	1.60	0.64	0.12

Base Material A-2

Head (ft)	Filter Size			
	3-4	6-8	16-20	30-40
5.25	-	1.19	0.53	1.56
10.50	-	7.75	0.18	0.22
15.75	-	5.27	0.30	0.45
21.00	-	20.63	1.56	0.58

Base Material A-3

Head (ft)		Filter Size			
	3-4	6-8	10-12	16-20	30-40
5.25	31.18	1.74	0.86	6.21	0.46
10.50	24.27	0.31	2.12	0.92	0.92
15.75	44.90	2.57	1.56	1.30	0.44
21.00	-	4.22	1.41	0.26	0.59

*Weight of material in first inch of filter layer neglected.

TABLE 5

Flow Through Test Samples at Various Heads (gals per min)

Base Material A-1

Head (ft)	Filter Size				
	3-4	6-8	9-10	16-20	30-40
5.25	0.085	0.0130	0.017	0.012	0.017
10.50	0.093	0.0245	0.030	0.019	0.027
15.75	0.136	0.0369	0.041	0.031	0.037
21.00	0.170	0.0470	0.053	0.044	0.048

Base Material A-2

Head (ft)	Filter Size			
	3-4	6-8	16-20	30-40
5.25	0.098	0.052	0.042	0.042
10.50	0.170	0.090	0.070	0.067
15.75	0.252	0.125	0.094	0.095
21.00	0.367	0.158	0.119	0.119

Base Material A-3

Head (ft)	Filter Size				
	3-4	6-8	10-12	16-20	30-40
5.25	0.090	0.047	0.032	0.045	0.020
10.50	0.115	0.069	0.052	0.073	0.040
15.75	0.128	0.095	0.076	0.106	0.046
21.00	0.238	0.119	0.101	0.137	0.068

TABLE 6

Per Cent Infiltration of Base Material Into Filter Layer*

(all values x 10^{-2})

Base Material A-1

Head (ft)	Inch Depth of Filter	Filter Size 3-4	6-8	9-10	16-20	30-40
5.25	1	64.98	22.02	27.58	8.20	5.00
	2	9.71	0.36	0.71	0.95	0.37
	3	4.31	0.19	0.87	0.96	0.38
	4	2.78	0.49	1.75	1.60	0.50
10.50	1	138.82	28.81	15.47	11.90	8.27
	2	22.82	1.06	1.15	1.10	0.35
	3	9.91	0.63	0.63	1.50	0.23
	4	5.79	1.00	0.27	1.50	0.64
15.75	1	111.32	29.93	15.47	11.90	8.27
	2	25.86	1.42	1.46	0.57	0.19
	3	9.91	0.63	1.12	0.32	0.20
	4	5.79	1.00	0.99	0.40	0.61
21.00	1	-	52.64	31.24	13.04	8.71
	2	-	4.22	3.24	0.92	0.14
	3	-	1.23	0.72	0.36	0.06
	4	-	0.88	1.01	0.62	10.53

(continued)

*Percentages are based upon weight of base material in each one inch increment of filter layer.

TABLE 6 (continued)

Per Cent Infiltration of Base Material Into Filter Layer
(all values x 10^{-2})

Base Material A-2

Head (ft)	Inch Depth of Filter	Filter Size 3-4	6-8	16-20	30-40
5.25	1	221.22	29.79	9.90	2.66
	2	48.09	1.54	0.18	1.04
	3	28.66	0.65	0.22	1.52
	4	15.66	1.23	1.08	1.83
10.50	1	214.50	103.69	9.88	4.66
	2	42.60	18.13	0.14	0.34
	3	22.06	3.98	0.09	0.16
	4	3.31	1.19	0.29	0.28
15.75	1	175.93	81.78	13.20	13.62
	2	69.72	10.97	0.20	0.68
	3	39.02	3.53	0.13	0.37
	4	24.75	1.24	0.61	0.47
21.00	1	-	151.03	11.60	3.90
	2	-	46.67	0.55	0.82
	3	-	12.97	0.38	0.34
	4	-	3.79	0.62	0.50

(continued)

TABLE 6 (continued)

Per Cent Infiltration of Base Material Into Filter Layer

(all values x 10^{-2})

Base Material A-3

Head (ft)	Inch Depth of Filter	Filter Size 3-4	6-8	10-12	16-20	30-40
5.25	1	-	50.59	13.75	3.45	5.75
	2	-	2.96	0.79	0.16	0.31
	3	-	1.04	0.95	0.10	0.32
	4	-	1.15	1.48	0.42	0.83
10.50	1	-	19.54	27.60	2.90	7.66
	2	-	0.60	3.61	0.97	1.15
	3	-	0.26	0.94	0.75	0.73
	4	-	0.11	1.46	1.16	0.80
15.75	1	-	71.00	46.48	11.50	12.66
	2	-	3.84	1.57	1.06	0.57
	3	-	1.70	1.51	1.17	0.32
	4	-	2.18	1.80	1.69	0.40
21.00	1	-	65.56	38.74	9.20	13.04
	2	-	7.64	1.45	0.16	0.92
	3	-	2.31	1.08	0.13	0.36
	4	-	1.25	1.66	0.48	0.62

TABLE 7

Piezometric Readings

Test			Piezometric Readings (inches Mg)					
			Piezometer 2		Piezometer 3		Piezometer 4	
Base	Filter	Head (ft)	Start	Finish	Start	Finish	Start	Finish
A-1	6-8	5.25	4.2	4.7	7.8	8.0	7.8	8.0
		10.50	7.5	6.5	12.7	11.0	12.7	11.0
		15.75	10.1	11.5	16.8	17.0	17.4	17.2
		21.00	9.7	15.6	22.6	22.8	22.6	22.9
A-1	9-10	5.25	3.9	3.1	6.5	7.7	6.7	8.2
		10.50	5.4	8.1	12.7	12.8	12.8	12.8
		15.75	8.1	11.2	17.8	17.4	18.1	17.6
		21.00	14.8	15.0	22.0	23.0	23.0	23.0
A-1	16-20	5.25	5.4	5.3	7.9	8.1	7.9	8.1
		10.50	8.2	8.4	13.3	12.8	13.3	13.0
		15.75	9.7	11.2	17.4	17.7	17.5	17.7
		21.00	13.9	8.9	22.9	22.5	23.0	22.7
A-1	30-40	5.25	4.8	5.0	7.3	7.6	7.4	7.7
		10.50	6.6	7.0	11.9	13.2	12.0	13.4
		15.75	13.2	14.3	16.9	17.5	17.2	17.6
		21.00	11.7	14.3	21.9	22.2	22.0	22.5
A-2	6-8	5.25	5.0	4.6	7.7	8.3	7.8	8.3
		10.50	6.2	8.6	12.3	12.5	12.4	12.8
		15.75	8.2	12.1	17.9	17.4	18.0	17.4
		21.00	14.2	15.8	22.3	21.8	28.4	27.9
A-2	16-20	5.25	5.4	5.6	8.1	7.8	8.1	7.9
		10.50	7.5	8.3	12.7	12.6	12.7	12.6
		15.75	13.3	13.5	17.9	17.9	17.9	18.0
		21.00	15.0	14.1	22.7	23.0	22.7	23.1
A-2	30-40	5.25	4.1	4.3	7.5	7.7	7.6	7.8
		10.50	6.8	7.0	12.6	12.2	12.7	12.5
		15.75	10.9	11.0	17.0	17.3	17.2	17.6
		21.00	11.8	14.9	22.5	21.6	22.7	22.0

(continued)

TABLE 7 (continued)

Piezometric Readings

Test			Piezometric Readings (inches Mg)					
			Piezometer 2		Piezometer 3		Piezometer 4	
Base	Filter	Head (ft)	Start	Finish	Start	Finish	Start	Finish
A-3	6-8	5.25	4.2	4.7	7.8	7.6	7.8	7.6
		10.50	8.8	9.1	12.9	13.1	12.9	13.1
		15.75	10.4	12.6	17.5	17.4	17.8	17.5
		21.00	15.3	16.6	22.7	22.5	22.7	22.6
A-3	10-12	5.25	2.6	2.9	7.8	7.8	7.8	7.8
		10.50	7.4	8.6	12.8	13.0	12.8	13.0
		15.75	11.3	11.6	17.6	17.6	17.6	17.7
		21.00	13.3	13.3	22.1	22.3	22.1	22.4
A-3	16-20	5.25	5.2	5.5	7.8	8.1	8.2	8.2
		10.50	8.6	7.3	12.4	12.8	12.5	12.9
		15.75	9.0	13.0	17.7	17.5	17.9	17.8
		21.00	15.7	-	22.2	-	22.3	-
A-3	30-40	5.25	4.9	4.3	7.5	7.6	7.6	7.8
		10.50	8.6	8.1	12.6	12.5	12.7	12.6
		15.75	10.8	11.4	17.2	17.1	17.2	17.1
		21.00	11.6	13.7	22.6	22.2	22.7	22.2

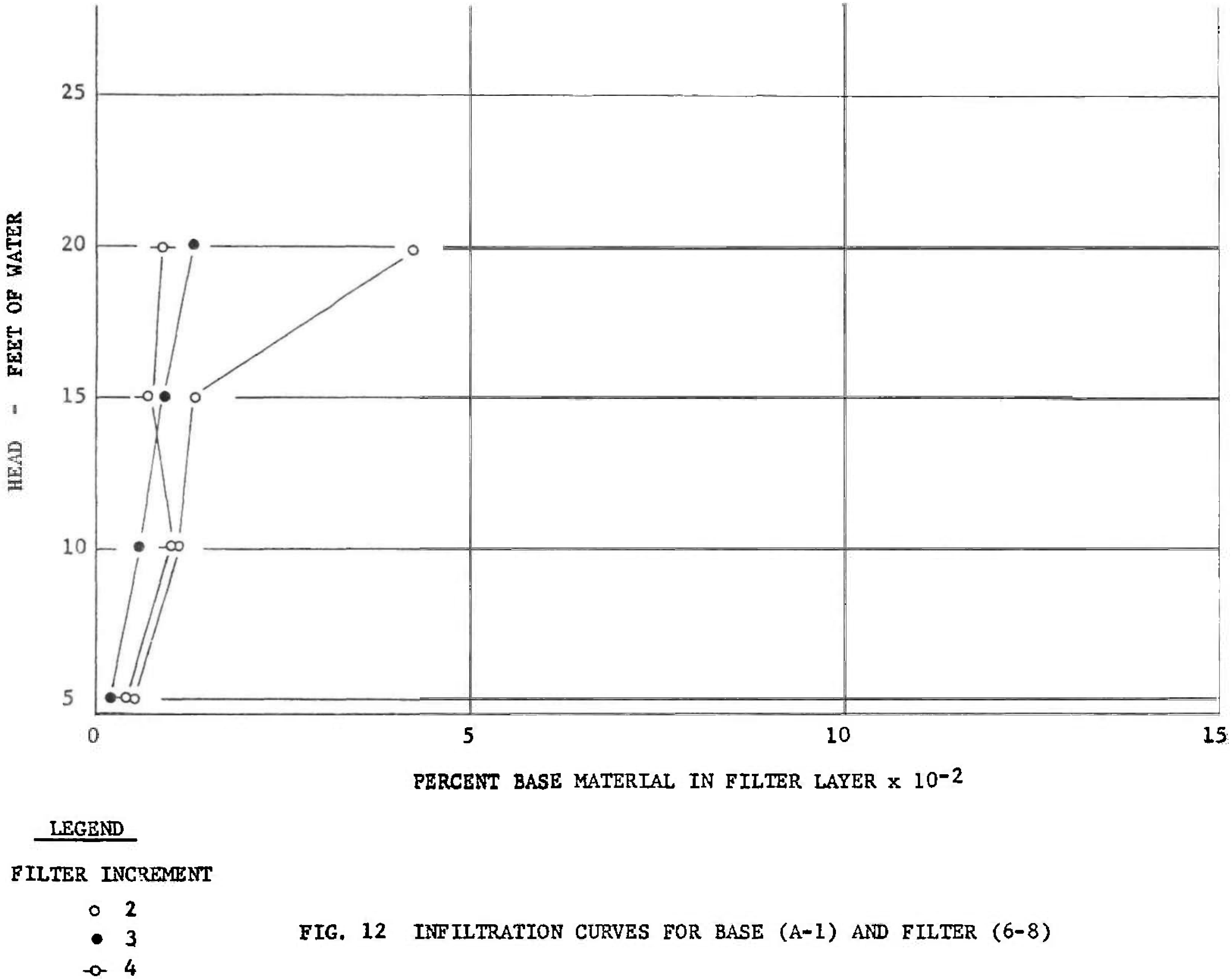
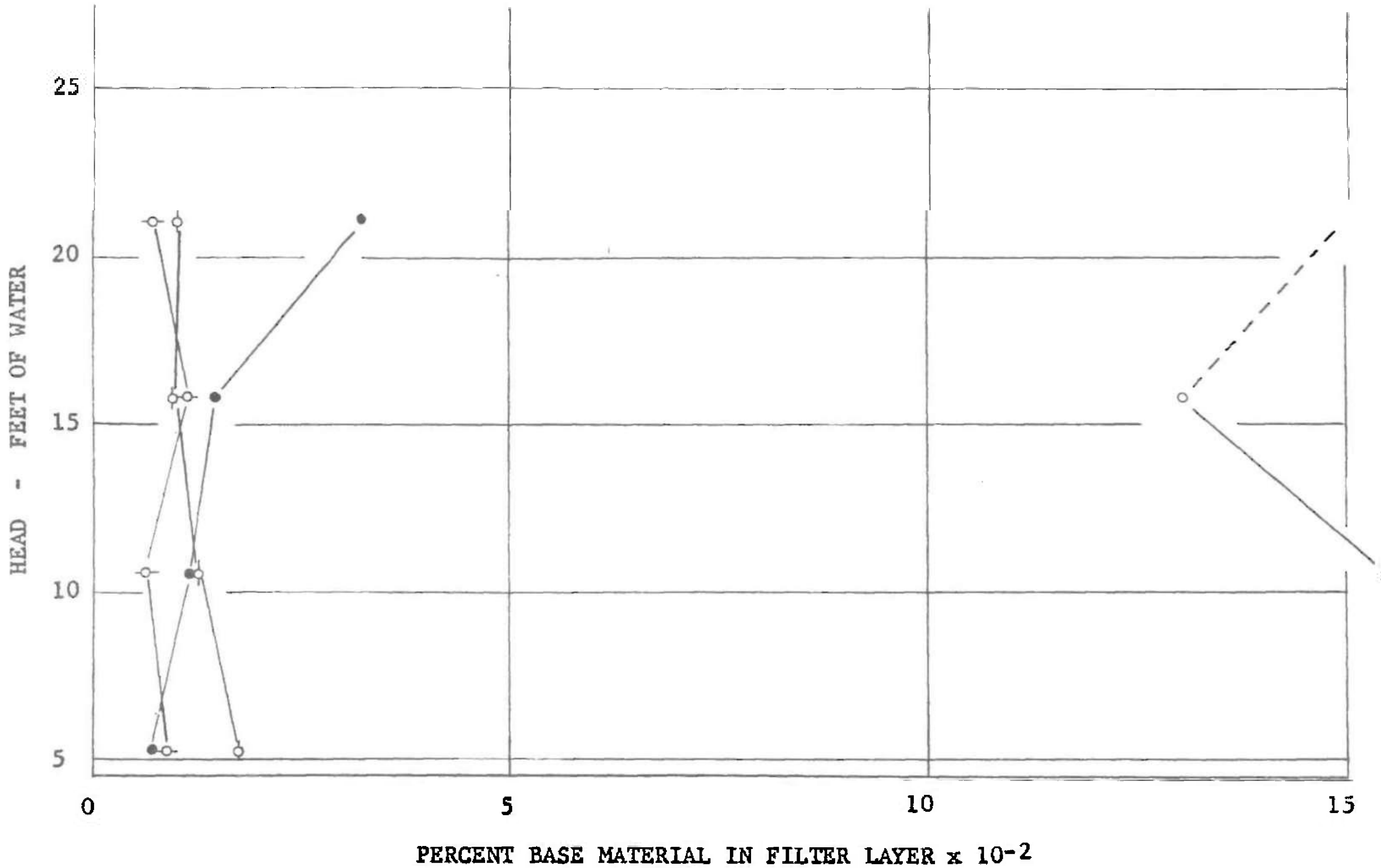


FIG. 12 INFILTRATION CURVES FOR BASE (A-1) AND FILTER (6-8)

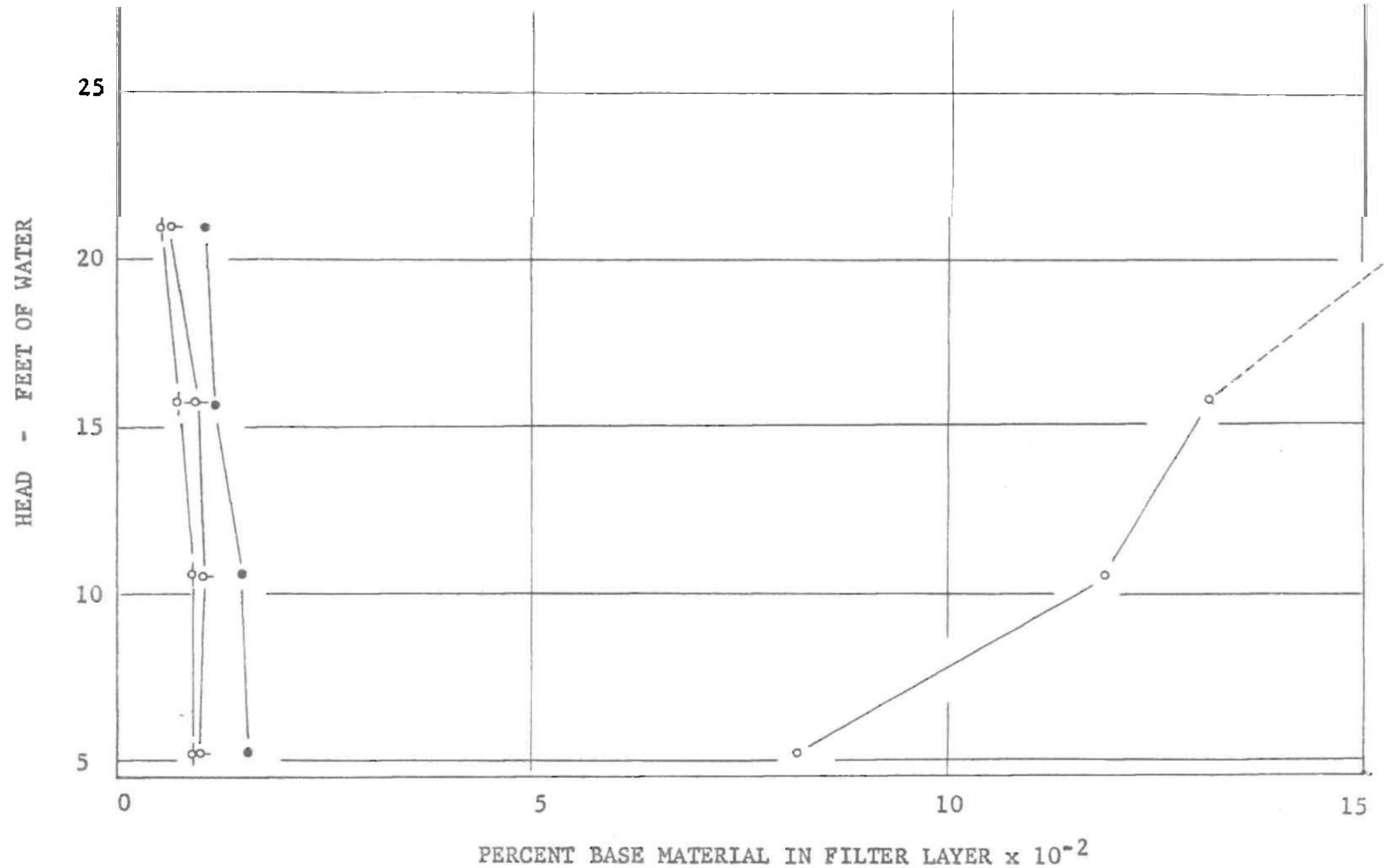


LEGEND

FILTER INCREMENT

- o 1
- • 2
- -o- 3
- ϕ 4

FIG. 13 INFILTRATION CURVES FOR BASE (A-1) AND FILTER (-10)



LEGEND

FILTER INCREMENT

- ○ 1
- ● 2
- -○- 3
- ȯ 4

FIG. 14 INFILTRATION CURVES FOR BASE (A-1) AND FILTER (16-20)

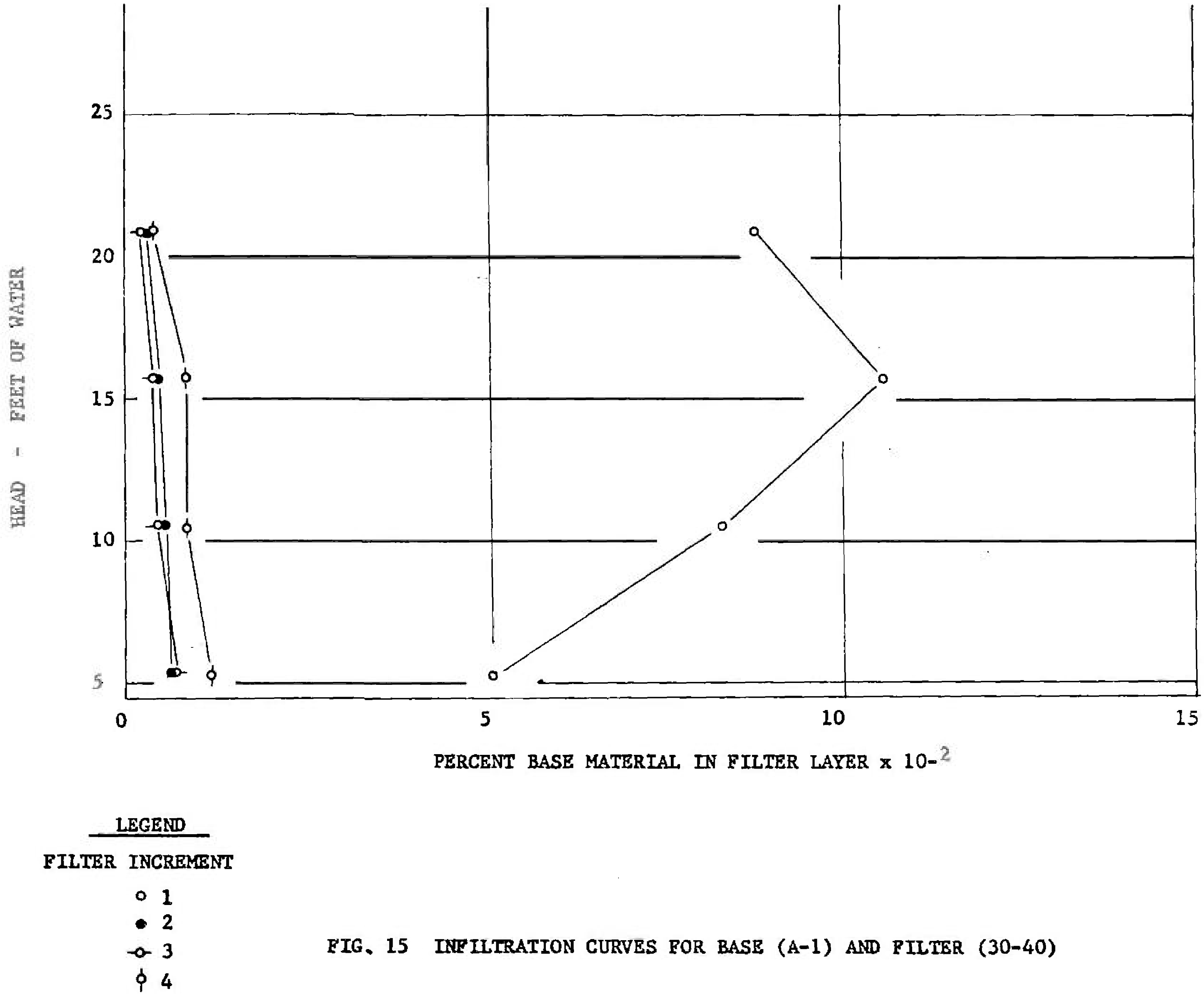
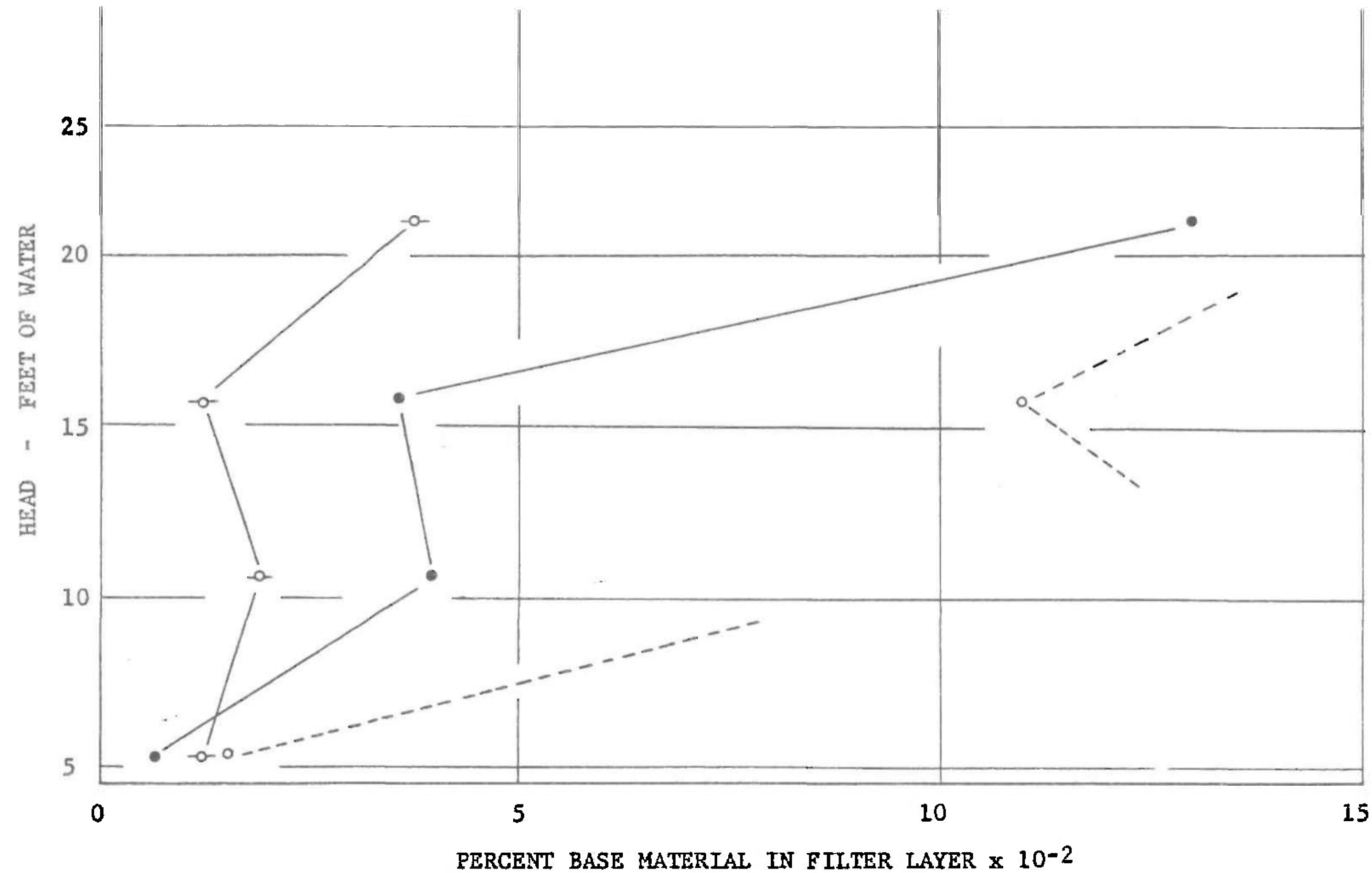


FIG. 15 INFILTRATION CURVES FOR BASE (A-1) AND FILTER (30-40)



LEGEND

FILTER INCREMENT

- o 2
- ● 3
- -o- 4

FIG. 16 INFILTRATION CURVES FOR BASE (A-2) AND FILTER (6-8)

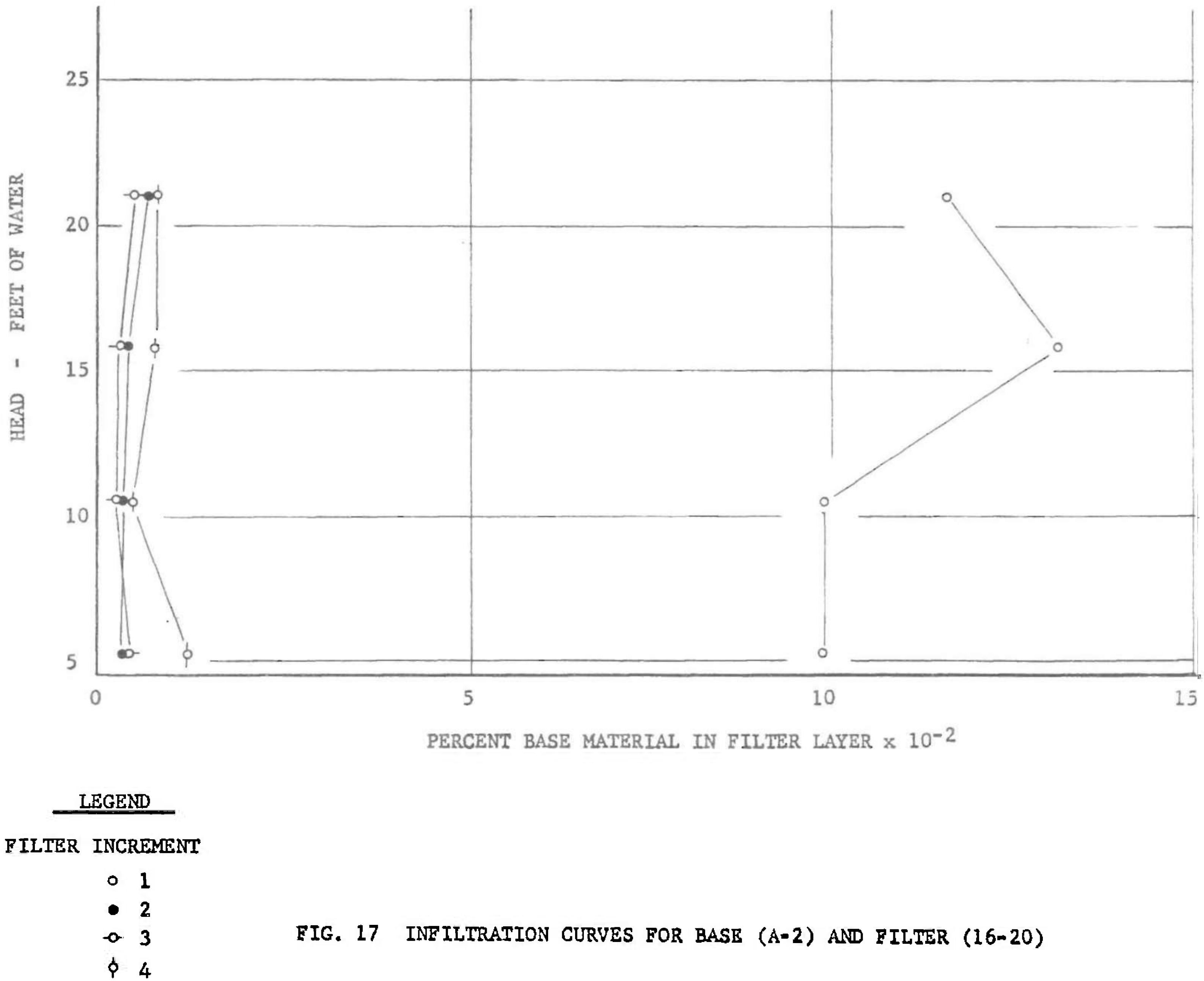
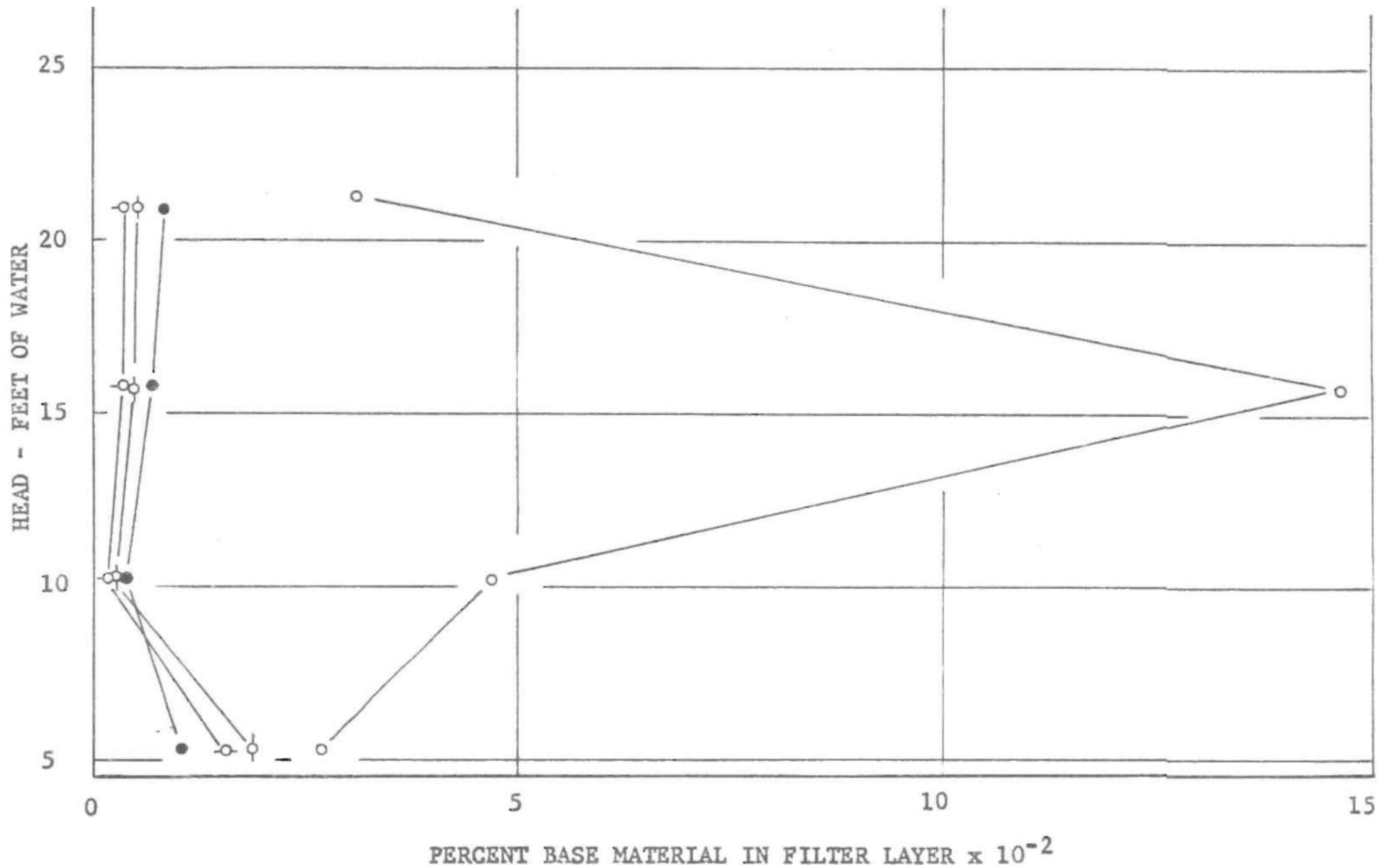


FIG. 17 INFILTRATION CURVES FOR BASE (A-2) AND FILTER (16-20)



LEGEND

FILTER INCREMENT

○ 1

● 2

-○- 3

ϕ 4

FIG. 18 INFILTRATION CURVES FOR BASE (A-2) AND FILTER (30-40)

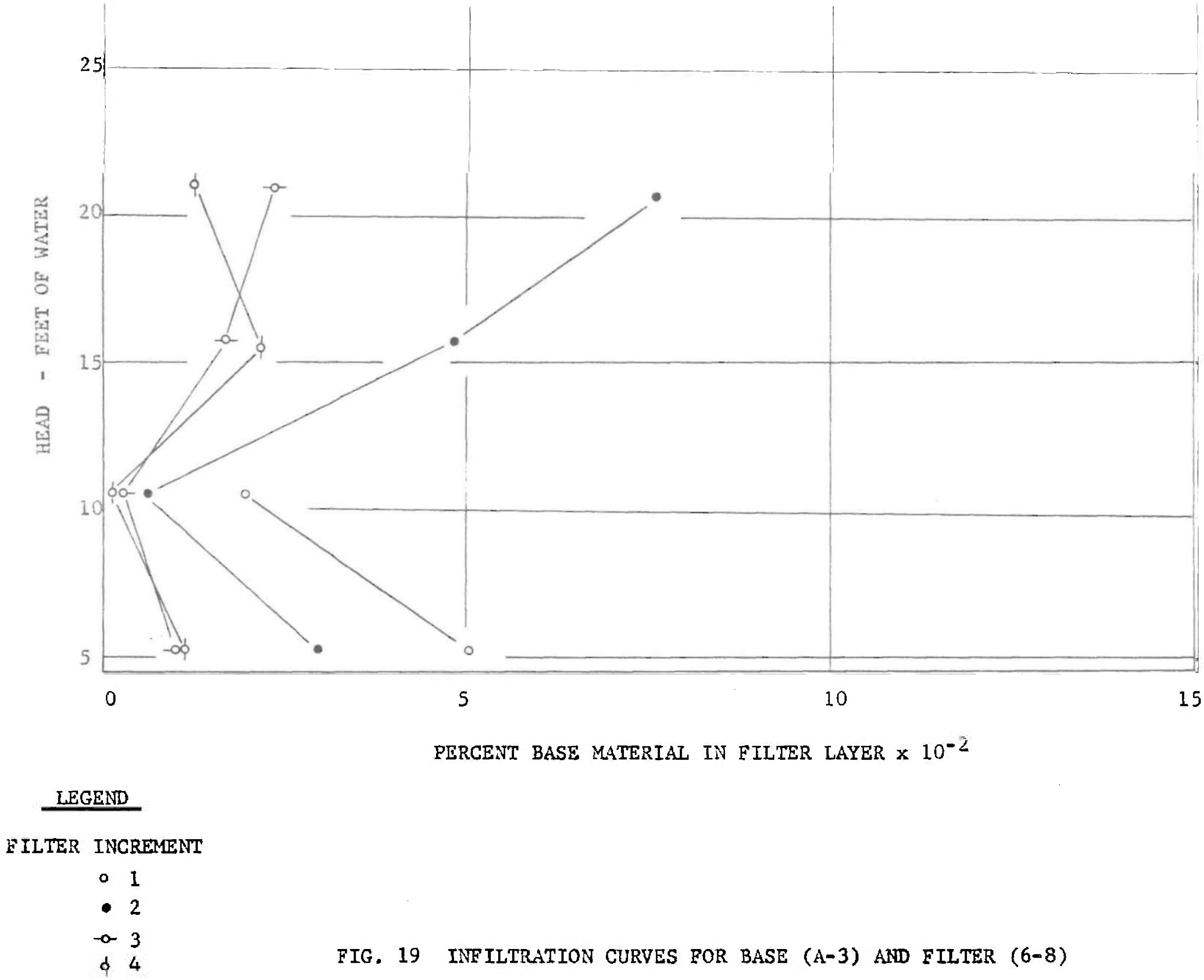
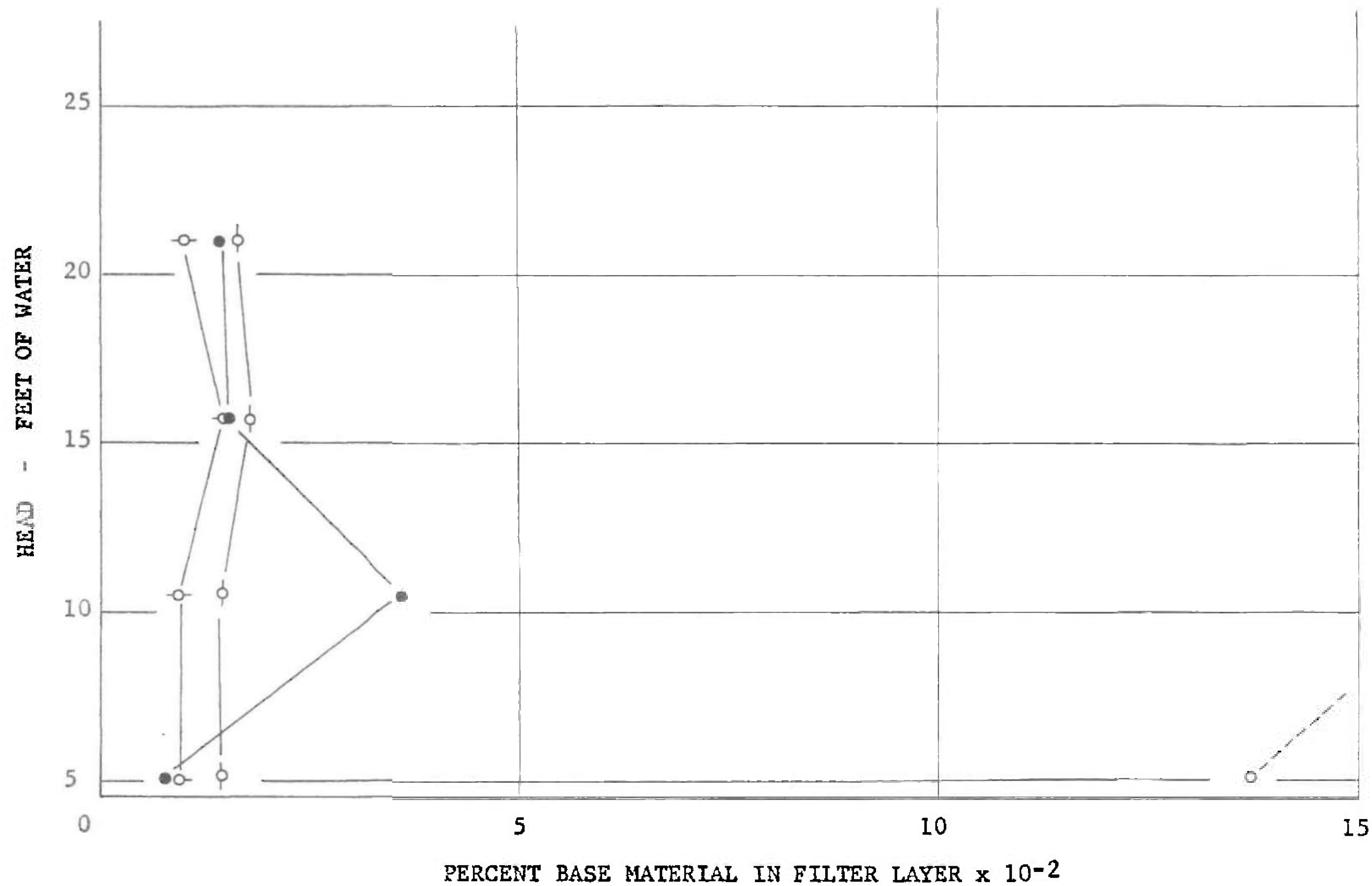


FIG. 19 INFILTRATION CURVES FOR BASE (A-3) AND FILTER (6-8)

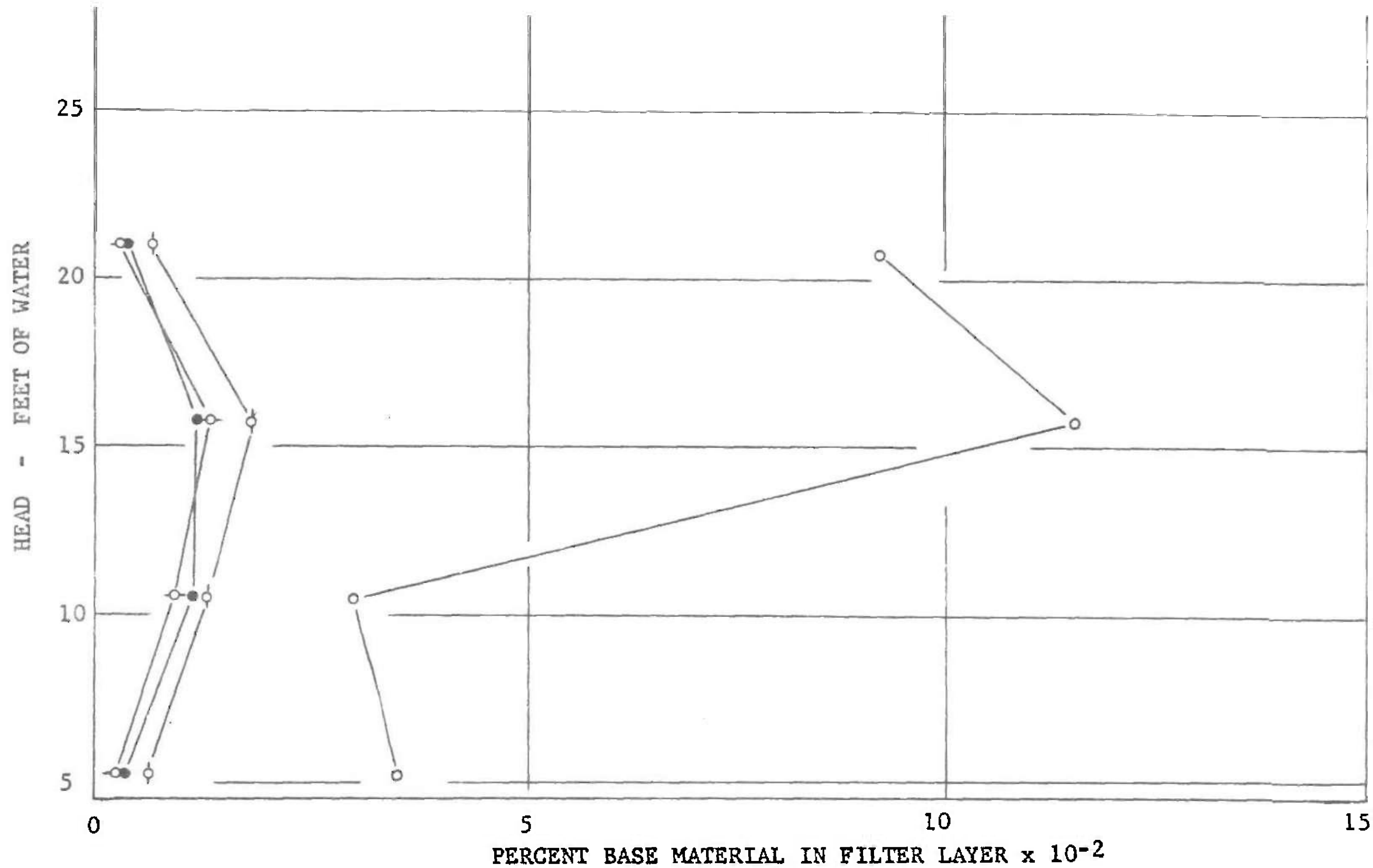


LEGEND

FILTER INCREMENT

○	1
●	2
-o-	3
ϕ	4

FIG. 20 INFILTRATION CURVES FOR BASE (A-3) AND FILTER (10-12)

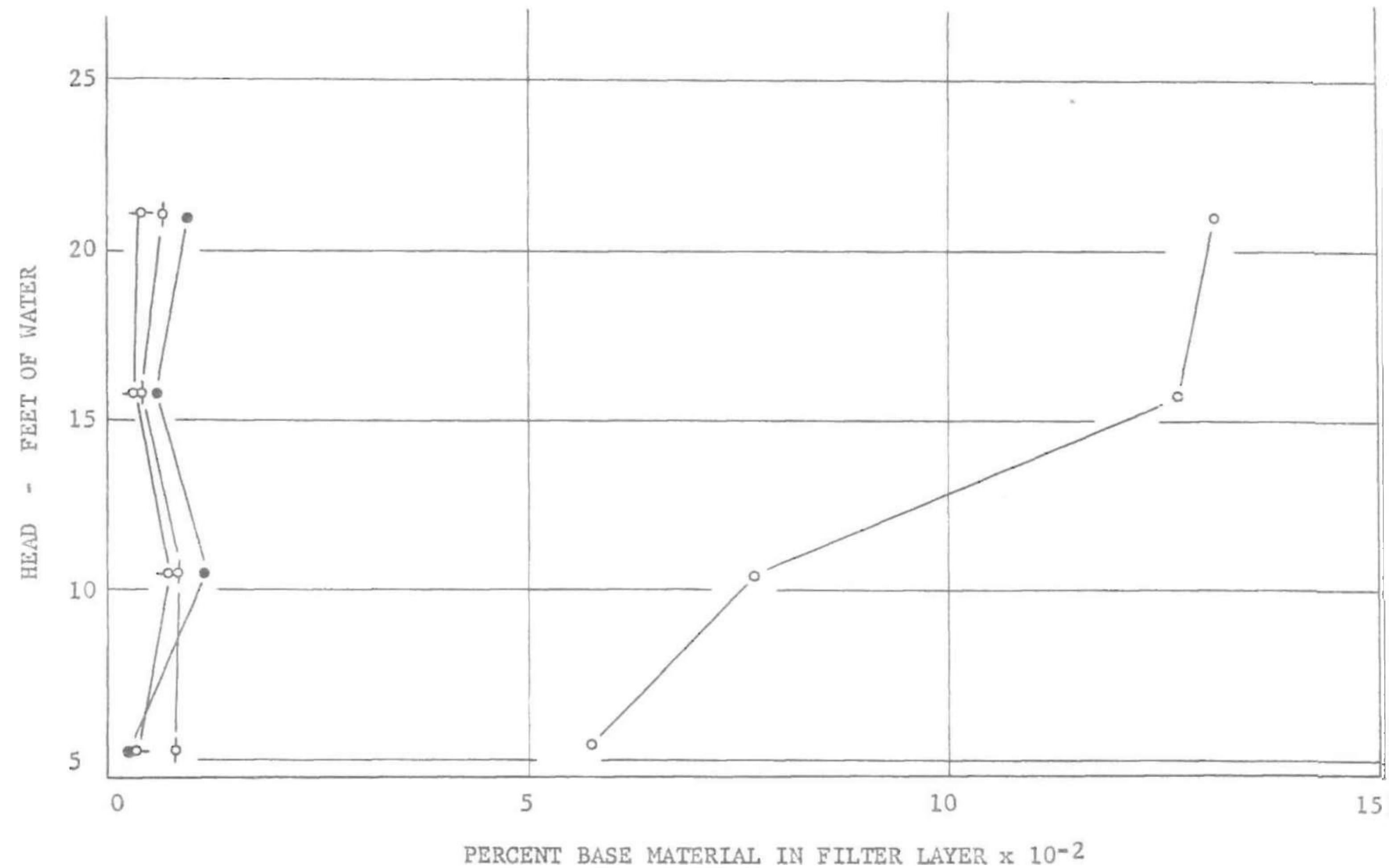


LEGEND

FILTER INCREMENT

- ○ 1
- ● 2
- -○- 3
- ϕ 4

FIG. 21 INFILTRATION CURVES FOR BASE (A-3) AND FILTER (16-20)



LEGEND

FILTER INCREMENT

- ○ 1
- ● 2
- -○- 3
- ϕ 4

FIG. 22 INFILTRATION CURVES FOR BASE (A-3) AND FILTER (30-40)

B I B L I O G R A P H Y

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